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Weathering and Subsurface Erosion in Granite at The Piedmont Angle, Balos, Sudan

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ABSTRACT

Sub-surface erosion is intensely active in weathered granite debris at the scarp foot of Jebel Qasim. Powerful flushes of sub-surface water after heavy rain remove much of the decomposing feldspar partly by solution and partly by mechanical eluviation. The sedentary debris gradually contracts as the feldspar is removed and when removal is nearing completion the debris may become compacted. The compacted debris occupies less than 40 per cent by volume of the granite from which it was derived.

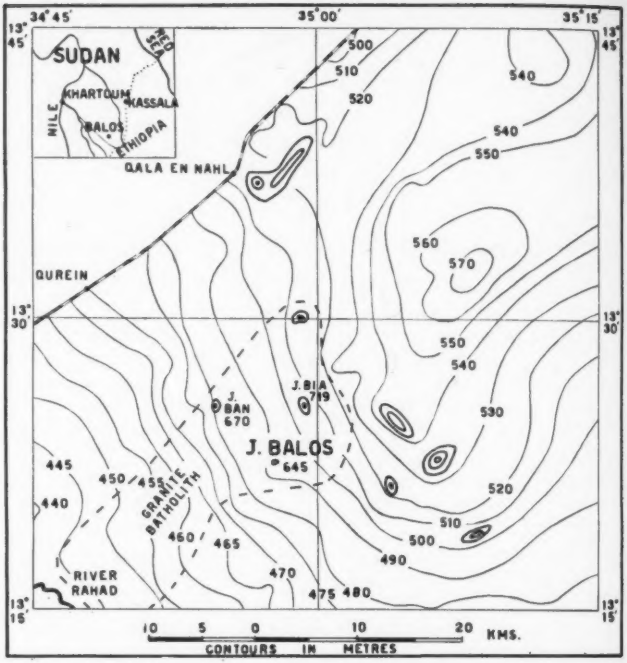
The upper fringing pediment around this hill is mantled by moist incoherent debris holding small local pockets of water which persist throughout the dry season. Annual recharge of this sub-surface water ensures intense weathering in the debris.

The combination of intense weathering and sub-surface erosion with ensuing contraction of the debris occurring just below the piedmont angle may be sufficient to explain the maintenance of this angle during slope retreat.

I. INTRODUCTION

STEEP isolated rocky hills fringed by sandy pediments and set in a monotonous clay plain are characteristic on the Ban-Balos granite batholith south of Qala en Nahl, Sudan (Text-fig. 1). These isolated hills show either a clear dome form with sheet structures visible under a thin cover of joint blocks or a central buttress of massive granite. Larger but lower areas of granite hills in the east show straight sheet jointing beneath a thin boulder cover and rarely show a dome form. The clay plains of the Balos area support a typical Acacia-tall grass forest. Rainfall is about 650 mm. (26 inches) annually, falling in thunderstorms mostly between May and October. The mean annual temperature is around 83·5 ° F. (28·5° C.).

Conspicuous angular junctions occur between the rocky hills, the sandy pediments, and the clay plains. A surface sequence of solid granite (including boulders), sand, and clay corresponds roughly with the sequence hill, pediment, and plain. In order to establish the



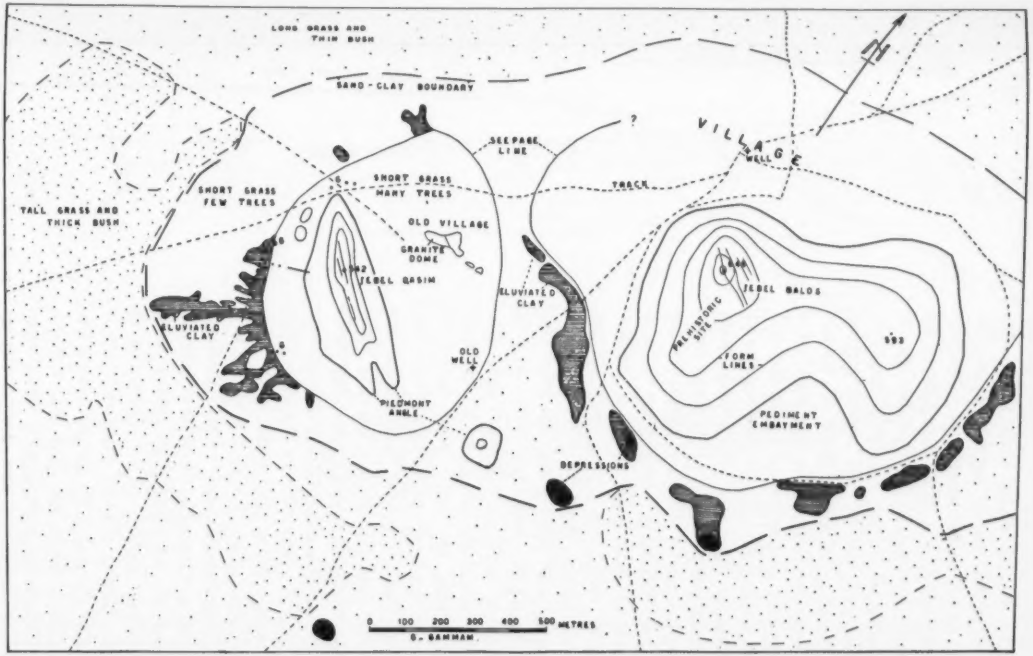
TEXT-FIG. 1.—Location map of Jebel Balos.

suspected genetic connection within and between these two sequences excavations were carried out near Jebel Qasim in March, 1957.

By studying the coarse-grained sedentary debris of a simple homogeneous rock (granite) it is possible to assess the role of sub-surface erosion during weathering development. Sub-surface erosion includes solution or chemical eluviation and mechanical eluviation or the movement of small size particles through the interstices of larger ones by circulating water. Whereas solution is known to occur on a large scale and quantitative data of its effects are available, mechanical eluviation has never been decisively proved. Apart from a detailed description of this small inselberg the main purpose of this paper is to demonstrate that not only does mechanical eluviation occur but also that its effects can be intense at the scarp foot of a granite hill mass.

II. JEBEL QASIM

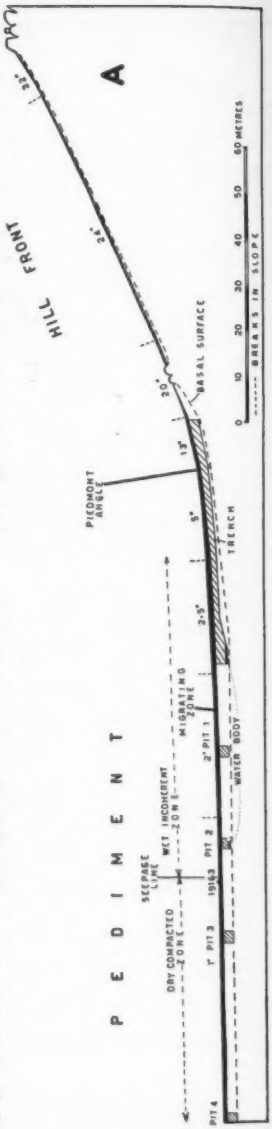
Jebel Qasim (about 550 metres O.D.) and Jebel Balos (645 metres)

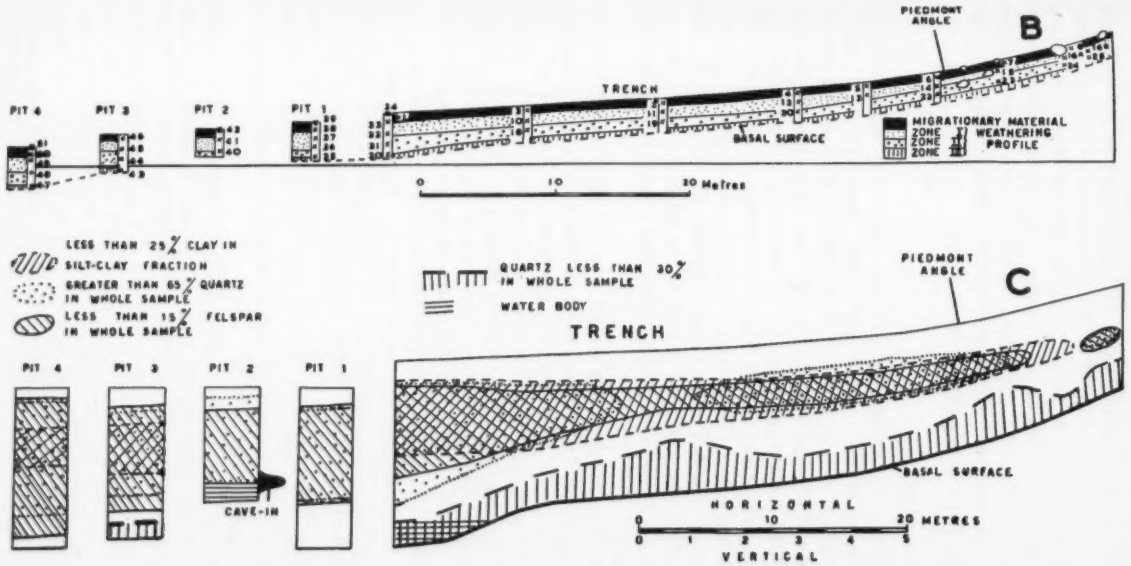


TEXT-FIG. 2.—Geomorphic map of Jebel Balos and Jebel Qasim, drawn from an aerial photograph.

together form an area of higher ground above the clay plain. Here this is at a level of 490 metres and slopes at 1 in 250 to 350 to the south-west. The geomorphology has been traced from an aerial photograph and is shown in Text-fig. 2. Jebel Qasim is an elongated hill, 600 by 200 metres aligned NW.–SE., standing some 45 metres above the plain. On the south-west side four distinct areas occur beneath the rocky summit. A boulder-strewn hillslope some 90–100 metres long descends abruptly on to an upper pediment of about the same width bearing a few boulders. Both these show a cover of short grass and many broad-leaved deciduous trees. Beyond this is a shallow slope of about 220–350 metres with short grass and few trees, and patchily veneered with a thin layer of dark grey-brown clayey silt. This terminates abruptly at its junction with the clay plain where a lunate area of thick bush and tall grass forms a partial ring around the sandy zone. Elsewhere the clay plain is covered with long grass and thin bush.

Nine slope elements were recognized from the rocky cliff to the clay plain (Text-fig. 3a). The rocky ridge with boulders up to $2\frac{1}{2} \times 6 \times 4$ metres is a cliff-erosion feature. Rock shedding from it causes a boulder-controlled slope at 32° for $12\frac{1}{2}$ metres with boulders about $2 \times 2 \times 1\frac{1}{2}$ metres in size. Below this the main hillslope is at 24° for nearly 60 metres with a few boulders scattered over its surface. Disintegrated granite with many compound fragments and much feldspar mantles the surface to a depth of about $2\frac{1}{2}$ feet of which the upper half appears to be migrationary. A narrow strip





TEXT-FIG. 3.—A The slope profile and excavations on the south-west side of Jebel Qasim. Drawn to natural scale.
B The trench and pits on Jebel Qasim, showing the layers of the regolith and the location of the 45 samples.
C Some variations in the properties of the debris in the trench and pits. Vertical scale exaggerated by four times.

about 18 metres wide sloping at 20° and bearing an isolated rocky outcrop passes into a slope of 13° for 12 metres to the piedmont angle.

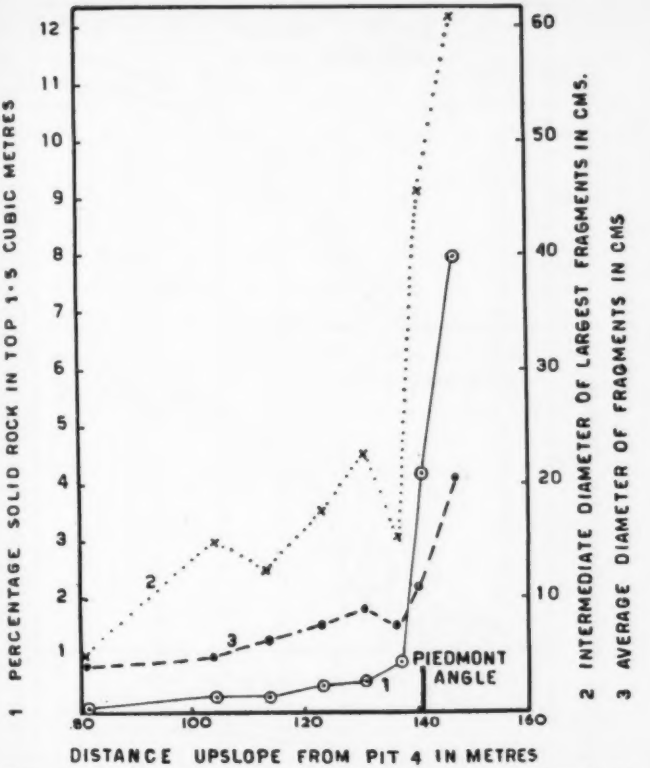
The piedmont angle is between 5 and 13° and the slope change occurs over a horizontal distance of 2 metres. The upper pediment shows slopes of 5°, 2½°, and 2° for distances of 20, 25, and 30 metres respectively. The lower pediment slopes at about 1° for 330 metres and meets the nearly flat clay plain in an abrupt angle.

The Excavations

The trench was commenced just below the rocky isolated outcrop on the lower hillslope and was continued downslope for 52 metres. Four pits were then excavated at 20, 40, 60, and 100 metres downslope from the end of the trench. In the top 5 feet (1½ metres) all hard rock encountered in the digging was put on one side into 8 piles and rough estimates were made of: the volume percentage of solid rock in the top 1½ cubic metres; the average diameter of the fragments; and the intermediate diameter of the largest fragment (Text-fig. 4). All these attributes showed a sudden change at the piedmont angle, the percentage of solid rock changing from less than 1 per cent to greater than 4 per cent.

In the field the profile was divided into four layers parallel with the ground surface and 45 representative samples were taken at the points on Text-fig. 3b. A top zone of migrationary material from 2 to 2½ feet thick contained vein quartz fragments from upslope and coincided very closely with the dark grey-brown surface soil. Below this was the weathering profile of sedentary debris which was divided into three zones. Zone I of reddish-brown quartzose gravel sometimes showed crude mottling near its base and was from 1½ to 5 feet thick; no textures of the parent granite were preserved. Zone II of pale brown arkosic gravel with a crude texture of the granite preserved in places, was from 2 to 5 feet thick. In the upper part of the trench it contained a few corestones. Finally Zone III of fragmented and iron-stained rock graded down rapidly to hard bedrock. The basal surface of solid rock was only encountered in Pit 3 after prolonged and difficult excavation of the Zone III material.

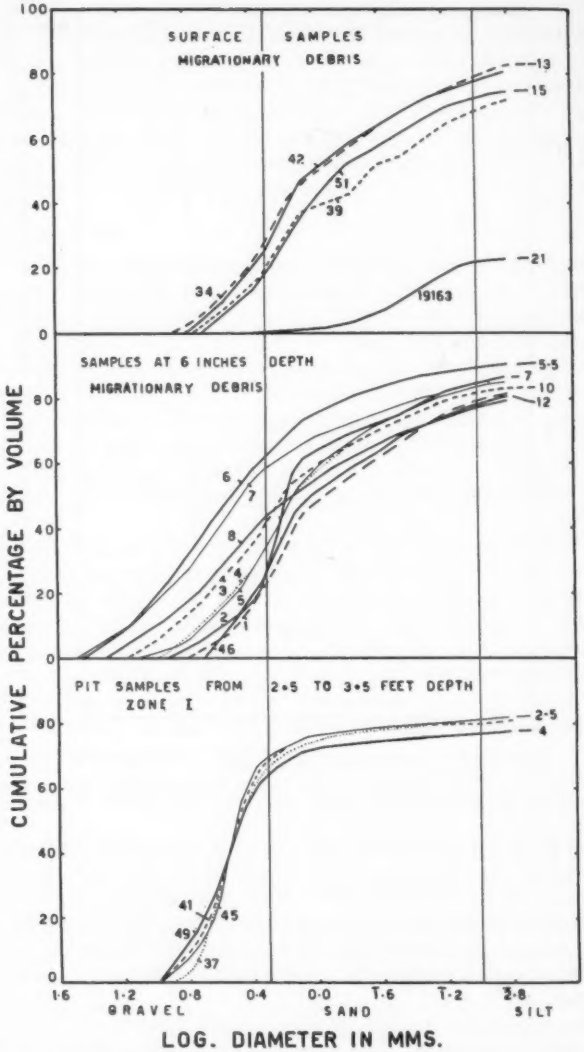
Two small water bodies were encountered during excavation near the base of the Zone II debris. One at the end of the trench at 10½ feet and the other at 5½ feet in Pit 2. In both cases about 1½ feet of quartzose gravel with very little silt and clay was encountered above the water level. This material was extremely unstable and caved in rapidly at the slightest disturbance. Some 20,000 gallons of water were extracted from these diggings between 24th March and the end of April. Pit 2 dried up just before the main rainy season commenced on May 11th.



TEXT-FIG. 4.—The " mobility " break at the piedmont angle shown by the sudden increase of solid rock in the top 1½ cubic metres of debris.

All the debris in the trench and Pits 1 and 2 was moist below about 2 feet and was easily excavated. That in Pits 3 and 4 was drier and more compact making excavation much more difficult. It was thus possible to distinguish an upper wet incoherent zone corresponding with the upper pediment from a dry compact zone downslope. The boundary passed between Pits 2 and 3 corresponding closely with the seepage line.

The seepage line is a thin strip along which water is said to stream out after intense rain. The local inhabitants call Jebel Qasim the " weeping hill ". This line separates the inner ring around the hill, with a sandy surface, many trees, and two growths of grass every year, from the outer ring with a thin patchy dark clayey silt cover, few



TEXT-FIG. 5.—Mechanical analysis curves for samples on the surface, at 6 inches depth, and between 2½ to 3½ feet depth in the pits. The percentages of clay in the samples are given on the right-hand side of the figure.

TABLE I.—THE COMPOSITION OF ALL THE SAMPLES COLLECTED

Specimen number	Depth in feet	Distance upslope from Pit 4	Size of largest Grain	Mechanical composition				Minimum percentage in whole sample of	
				Gravel	Sand	Silt	Clay	Quartz	Feldspar
		m.	mm.						
19163	0	53	9	0	21	58	21	20	1
1	0·5	101	7	24	55	—21—		57	24
2	0·5	111	8	27	57	—16—		55	31
3	0·5	121	15	41	41	8	10	61	22
4	0·5	131	9	35	46	—19—		56	27
5	0·5	136	14	36	47	—17—		47	38
6	0·5	141	30	62	28	4·5	5·5	51	40
7	0·5	146	30	59	24	10	7	45	39
8	0·5	151	20	44	33	—23—		39	40
10	3	110	9	58	20	—22—		70	9
11	3	120	9	55	20	19·5	5·5	63	13
12	3	130	12	60	18	—22—		71	7
13	3	135	9	74	11	—15—		78	8
14	3	140	10	60	17	18	5	69	9
15	3	145	10	53	21	20	6	65	10
16*a*	3	150	20	73	13	—14—		61	26
16*b*	3	152	14	62	18	—20—		67	14
18	6	110	10	61	20	—19—		64	18
19	6	120	15	51	24	17·5	6·5	27	48
20	6	130	10	50	25	—25—		51	25
22	5	140	12	44	32	17	7	43	34
23	5	146	18	63	23	8	6	28	59
24	6	149	15	59	26	—15—		44	42
25	5	152	25	64	21	—15—		28	57
30	10·5	100	18	58	25	11	6	27	57
31	7·5	100	10	70	20	4·5	5·5	75	16
32	5	100	10	71	14	11·5	3·5	80	5
33	2	100	8	65	16	15·5	3·5	71	11
34	0	100	8	27	52	8	13	49	32
35	8·5	80	10	63	20	—17—		57	26
36	6	80	10	65	16	—19—		73	10
37	3·5	80	8	66	15	—19—		80	2·5
38	1·8	80	10	56	21	—23—		64	14
39	0	80	6	19	49	—32—		53	18
40	5·5	60	11	83	14	— 3—		96	0·5
41	2·5	60	10	68	12	—20—		80	0·5
42	0	60	7	26	51	—23—		60	20
43	9	40	30	72	18	7	3	28	64
44	6	40	10	65	14	15	6	68	9
45	3	40	10	70	11	16·5	2·5	81	1
46	0·5	40	5	26	51	11	12	62	17
47	9·3	0	11	55	21	17·5	6·5	61	15
48	6·3	0	8	61	15	17	7	71	6
49	3·3	0	10	64	13	19	4	76	2
50	1·5	0	7	46	31	14·5	8·5	69	9
51	0	0	5	19	53	13	15	56	18

trees, and only one growth of grass every year. The junction on the ground is 7 metres downslope from Pit 2 and is very clearly seen on the aerial photograph.

The thin dark clayey silt occurs as a partial ring around the hill with finger-like projections extending outwards down the lower pediment slope. The " fingers " are slight depressions, about 10 inches deep across some 25 metres, and a notable concentration of heavy dark minerals occurs in them. One selected specimen (19163) was collected from this.

Laboratory Procedure

All 46 specimens were halved and the fine fraction washed through a 200-mesh sieve (aperture 0·076 mm.). The coarser fraction was

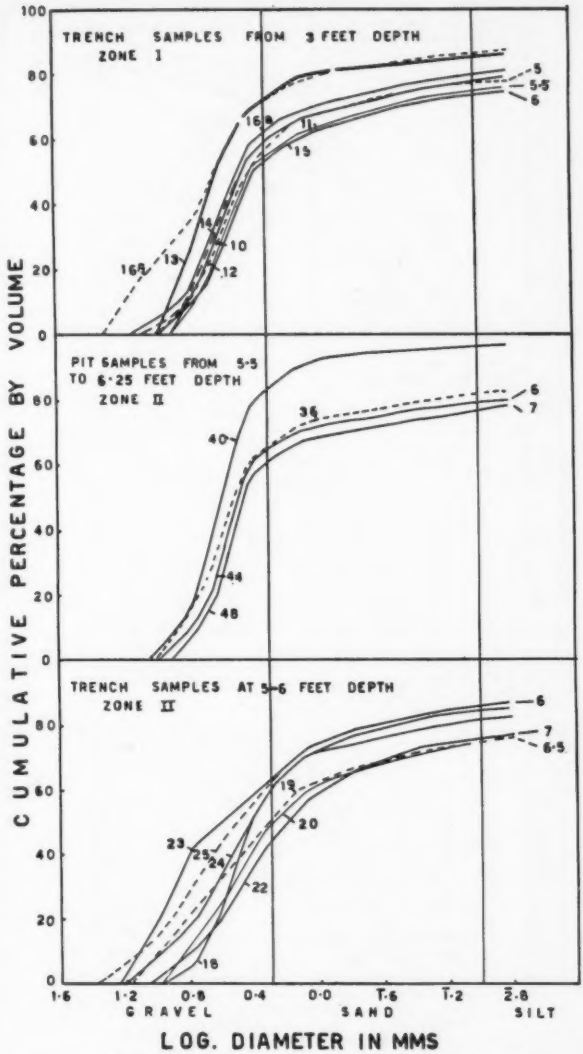
TABLE II.—SOME SELECTED AVERAGES FROM TABLE 1

	Mechanical composition				Minimum percentage in whole sample of	
	Gravel	Sand	Silt	Clay	Quartz	Feldspar
Surface samples from 0–100 m. upslope. Nos. 34, 39, 42, 51	23	51	11	15	54·5	22
Pit samples 2½–3½ feet depth. Nos. 37, 41, 45, 49 . . .	67	13	16	4	79	1·5
Pit samples 5½–6½ feet depth. Nos. 36, 40, 44, 48 . . .	68·5	15	11·5	5	77	6
Trench samples at ½ ft. depth. Nos. 1–8 inclusive .	41	41	9	9	51	33
Trench samples at 3 feet depth. Nos. 10–16b inclusive .	62	17	16	5	68	12
Trench samples at 5–6 feet depth. Nos. 18–25 (but no No. 21) . . .	56	24	13	7	41	40·5

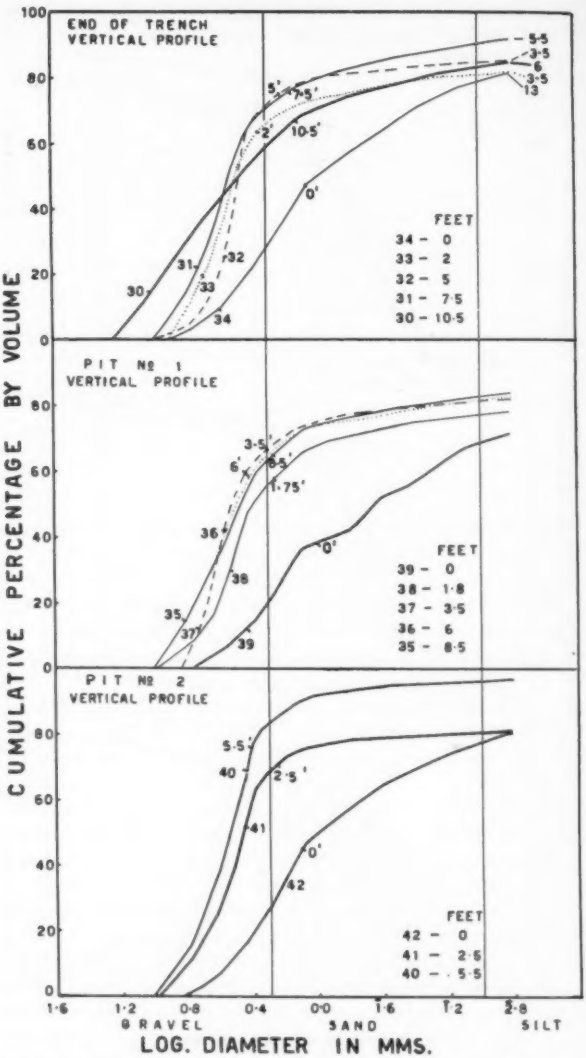
mechanically analysed by volume into fractions greater than 12, 6, 2·4, 0·6, 0·42, 0·30, 0·21, 0·15, and 0·076 mm. respectively. Then the ratio of quartz to feldspar was determined in all fractions by counting 100 grains. In the coarser fractions only an estimate could be made owing to the abundance of compound grains. From these ratios the minimum percentage of quartz and feldspar was found for the whole sample (Table I). It was not possible to make accurate measurements of the content of quartz and feldspar in the silt and clay fractions. Biotite was only apparent in five samples of disintegrated rock (19, 23, 25, 30, and 43) and even in these it made up less than 1 per cent of the coarse fraction and so its presence was ignored.

The fine fraction was stood for one day and the clear water decanted off, it was then put in the sun until thoroughly dry and then weighed. By assuming the specific gravity of this fraction to be 2·6 its volume was calculated. Thus a curve of cumulative percentage by volume against logarithm of diameter in mm. could be plotted (Text-figs. 5, 6, 7, and 8). Five grammes of the fine fraction of 24 samples were decanted by Dr. G. A. Worrall to determine the silt:clay ratios. The size limits between gravel, sand, silt, and clay were set at 2, 0·1, and 0·005 mm. respectively and these divisions are shown on the graphs.

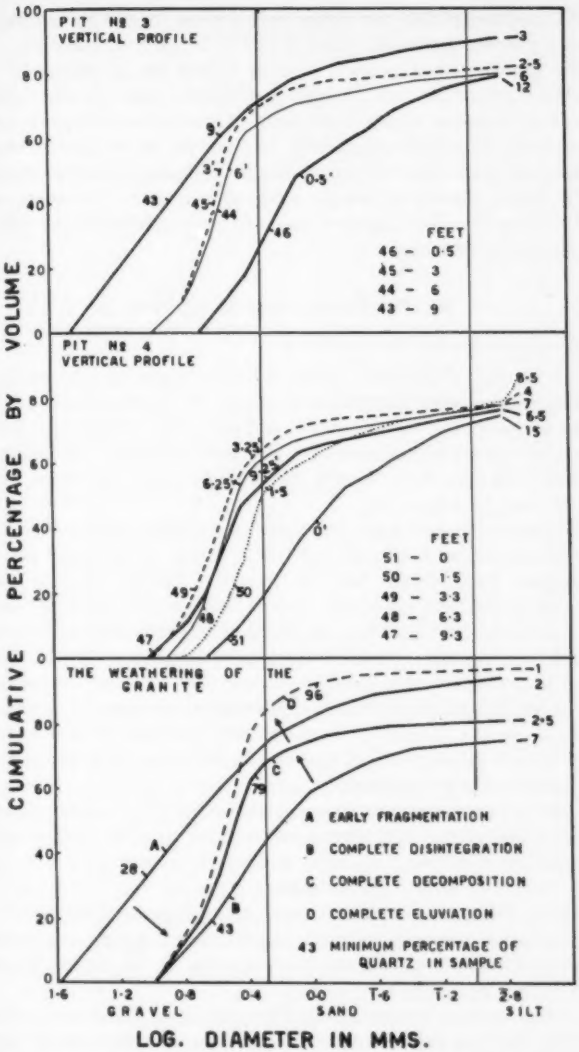
Specific gravity determinations were made on the samples of dry compacted debris (36, 37, 41, 44, 45, 47, 48, and 49), all were very close to 2·40. The samples 36, 37, and 41 only became compacted after transportation to Khartoum.



TEXT-FIG. 6.—Mechanical analysis curves for samples in the trench at 3 and 5–6 feet depth, and in the pits at 5½ to 6¼ feet depth.



TEXT-FIG. 7.—Mechanical analysis curves. Vertical profiles at the end of the trench and in Pits 1 and 2.



TEXT-FIG. 8.—Mechanical analysis curves. Vertical profiles in Pits 3 and 4, and four generalized curves depicting the weathering of the granite.

The mechanical analysis curves were plotted in groups selected to show significant variations (Table II and Text-figs. 5, 6, 7, and 8).

The coarse-grained granite of Jebel Qasim has a granularity of between 3 and 6 mm. with an average of about 4 mm. In thin section it is seen to consist almost exclusively of microcline and quartz with quite minor oligoclase and biotite. Six counts, using ruled celluloid grids on large cut faces of three specimens collected from near the top of the trench, showed an average mode of 24 quartz, 72 feldspar, and 4 dark minerals. The variation was only plus or minus 2 per cent in the figures for feldspar.

III. Weathering and Eluviation

(*a*) *Disintegration and Decomposition*

Iron staining of the fresh rock is followed closely by a coarse fragmentation into large compound fragments with subordinate simple grains of microcline, biotite, quartz, and some clay. This stage is well shown by sample 43 collected at 9 feet depth in Pit 3. The feldspar content is 64 and that of quartz 28, while the sample contains 7 per cent silt and 3 per cent clay.

The large compound fragments break up into their component grains and the microcline is increasingly parted along its cleavages until a thoroughly disintegrated debris is formed. Sample 22 is a good example of this with gravel 44, sand 32, silt 17, and clay 7 per cent. The quartz content was 43 per cent and the feldspar content 34 per cent.

Both fragmentation and disintegration are accompanied by weathering of the microcline and biotite to silt and clay. Further decomposition of the microcline depletes the sand fraction causing the formation of a silty gravel. Typical products are the pit samples at 2½ to 3½ feet depth with 67 gravel, 13 sand, and 16 silt, and 4 clay with contents of 79 quartz and only 1½ feldspar.

Removal of the silt and clay both as small particles and in solution further increases the quartzose gravel content and in extreme cases may give rise to 83 gravel, 14 sand, and only 3 per cent of silt and clay, with contents of 96 quartz and 1½ feldspar.

Text-fig. 8 (the lowest section) shows the changes that take place in the mechanical composition of this granitic debris during weathering. The four curves are generalized from samples 43, 22, pit samples at 2½ to 3½ feet depth, and sample 40.

In order to show the variations of four attributes a sectional profile (Text-fig. 3c) was drawn. A quartz content of less than 30 per cent in the whole sample delimits the fragmented rock while the area of most intense weathering is shown by a quartz content of over 65 per cent and a feldspar content of less than 15 per cent. The area for

TABLE III.—CALCULATED LOSSES BY SOLUTION AND MECHANICAL ELUVIATION

	Parts of debris per 24 parts of quartz			Loss from original rock		
	Quartz	Feld-spar	Silt & Clay	Solu-tion	Mech. Eluv.	Total
Original rock . .	24	76	0	0	0	0
Disintegrated rock, samples Nos. 19, 23, 25, 30, 43 .	24	49	13	13·5	0·5	14
Above piedmont angle, samples 15, 16a, 16b, 23, 24, 25 .	24	17	8	29·5	21·5	51
Below piedmont angle, samples 12, 14, 20, 22 . . .	24	8	9	34	25	59
Pit 4, 3 – 9¼ feet, samples 47, 48, 49	24	3	8	36·5	28·5	65
Zone of compaction, samples 37, 41, 45, 49 . . .	24	0·5	6	37·5	32	69·5
Sample 40 . .	24	0	1	38	37	75
Complete differentiation . . .	24	0	0	38	38	76
All sedentary samples, 10–25, 30–32, 35–37, 40, 41, 43–45, 47–49	24	8	7	34	27	61
All migrationary samples, 1–8, 33, 34, 38, 39, 42, 46, 50, 51	24	11	8	32·5	24·5	57

less than 25 per cent clay in the silt-clay fraction also coincides closely with the area of greatest weathering.

Solution or Chemical Eluviation.—If we assume that the quartz is only slightly disintegrated during weathering and not decomposed then we may use it as a constant by which to assess the losses that occur. The original content of 24 per cent quartz in the rock may become as high as 96 per cent in the residual debris giving a loss of 75 per cent of the original rock. How is this material lost?

Neglecting the subordinate content of oligoclase and biotite the microcline will give rise to silt and clay size particles. These will consist of some finely divided microcline, and some clay mineral, and will be accompanied by a solution containing potassium and silica. The material in solution can migrate with the flow of the sub-surface water and so will be washed away downslope. But solution alone can hardly remove all the non-quartzose material constituents. If it could then solution depressions on granitic rocks should have been recorded long ago. But solution depressions have only been found on more

basic igneous rocks, e.g. hornblende-plagioclase rocks or diorite in North Carolina by LeGrand (1952). He records one to two-foot depressions due to differential weathering on profiles from 10 to 50 feet thick. Their small size seems to indicate that only a subordinate portion of the rock can be removed in solution.

Mechanical Eluviation.—A minimum quartz content in the whole sample is measured. Thus the minimum total loss of material as a volume percentage of the original rock can be calculated (Table III, last column). But in order to assess the amount of mechanical eluviation in this loss it is necessary to make various assumptions whereby the maximum amount of removal by solution is allowed for.

To do this the parts of the residual debris per 24 parts of quartz are calculated as two fractions: feldspar measured as grains larger than 200 mesh, and the remaining silt and clay. For example, the average of six sedentary samples collected from above the piedmont angle showed 49 quartz, 35 feldspar, and 16 silt and clay (containing unmeasured quartz and feldspar). These scale down to 24, 17, and 8 respectively. Since the original rock contained 76 parts of non-quartzose material the total loss is then at least 76 — (17 + 8), i.e. 51 per cent by volume of the rock. The number of parts of feldspar and biotite in the original rock which have gone to form a silt and clay fraction is then 59 (i.e. 76 — 17).

If we wish to allow for the maximum amount of solution then we shall assume that all these 59 parts of the original rock have been completely decomposed and thoroughly leached. By assuming that up to half of the original non-quartzose constituents may be removed in solution the loss from the original rock by leaching may be up to 29½ per cent, and the loss by mechanical eluviation will be 21½ per cent or over.

If it had been assumed that all or part of the silt and clay fraction was composed of feldspar and quartz then the total loss would be greater, the loss by solution less, and the loss by mechanical eluviation much greater. It is unlikely that more than half of the microcline could be removed in solution. If less is lost in this way then the mechanical eluviation will be greater. Moreover if the remaining portion of the decomposed feldspar produces more than an equivalent volume of clay mineral, mechanical eluviation will again be greater; but in this case it would not affect the figure for the loss already calculated as a fraction of the *original rock*.

A glance at Table III shows that the results are indicative of the kind of changes we might expect; much solution and little mechanical eluviation in the fragmented and disintegrated rock, increased percentages of loss by mechanical eluviation downslope, and extreme losses in the Zone I material and sample 40.

(*b*) *The Weathering Profile*

From the data presented it is seen that the provisional field division into four layers has been fully justified. The sandy migrationary material shows a high content of feldspar and clay. Gravelly Zone I debris has low feldspar and clay contents and high quartz values. Zone II is similar to Zone I as a gravelly debris but the contents of quartz, feldspar, and clay are moderate. Finally coarse gravelly Zone III debris has subordinate quartz, dominant feldspar, and moderate clay. Moreover graphs of the vertical profiles in the pits and at the end of the trench show a sharp break between the migrationary and sedentary debris, with reversals occurring in the contents of clay, feldspar, and gravel (text-figs. 9 and 10).

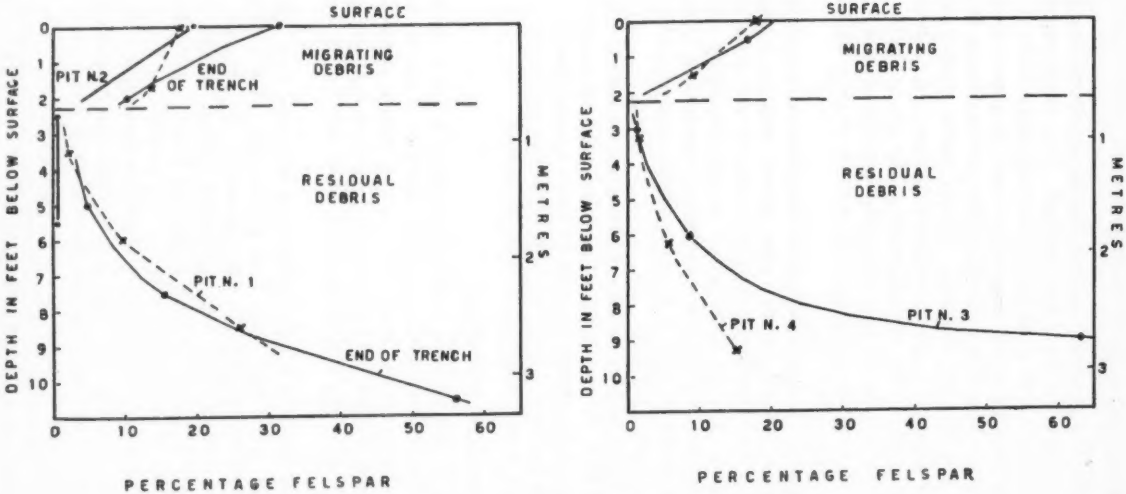
More gradual but equally significant changes occur downslope. The migrationary material becomes finer grained with less feldspar and more clay; the difference between the three sedentary zones becomes more distinct; and the whole profile is more thoroughly weathered. Thus the content of feldspar in the sedentary zone between 3 and 6 feet above the piedmont angle is 35 per cent while between 3 and 9½ feet in Pit 4 it is only 8 per cent.

Apart from a sudden increase in the corestone content above the piedmont angle the properties of the debris show no sudden change and persist in diminishing form for 18 metres upslope from it. Here, apart from the isolated rocky outcrop, there is a rapid change to Zone III material at or immediately beneath the surface.

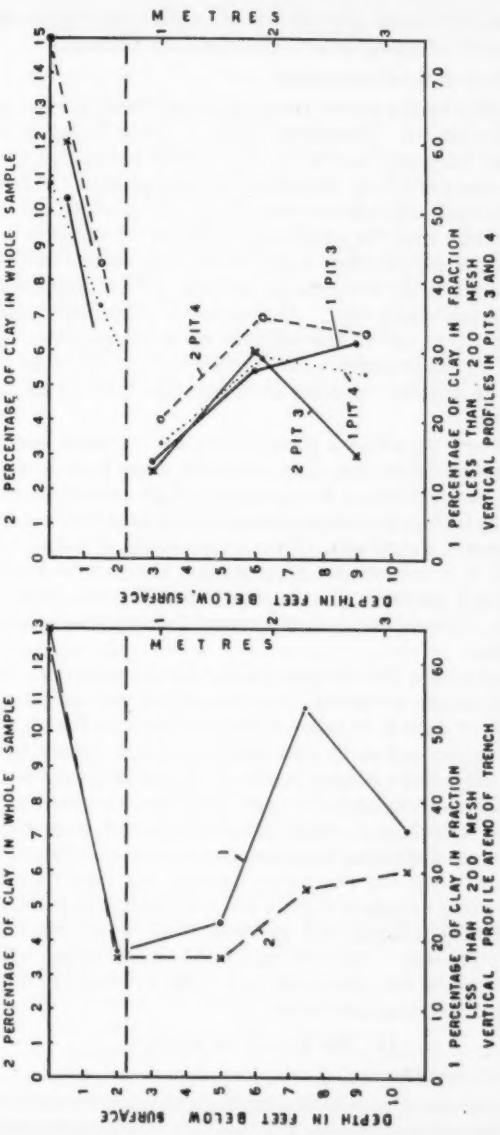
(*c*) *The Compaction of the Debris*

Samples 45 and 49, from 3 and 3½ feet depth in Pits 3 and 4, were quite dry and compact when excavated. Samples 37 and 41, from 3½ and 2½ feet depth in Pits 1 and 2, were, on the contrary, incoherent and moist when excavated, but after reaching Khartoum these two samples were found to be dry and compact and could only just be disaggregated by hand.

In all four cases the feldspar content was very small, ½ to 2 per cent, and that of quartz very high, 76 to 81 per cent. The total loss of material from the original rock was calculated as 69½ per cent. Their mechanical analysis curves were remarkably similar (Text-fig. 5) with an average of 67 gravel, 13 sand, 16 silt, and 4 clay. Either the binding properties of their clay on drying is very powerful or they are just of the right mechanical composition to become thoroughly compacted. Since the clay content is so small it is probable that mechanical composition has to be within certain close limits to allow the binding powers of the clay to be spread evenly throughout the debris. Small fragments of this compacted debris disaggregate rapidly in water. The specific gravity of the compacted debris was 2·4, thus with a loss of



TEXT-FIG. 9.—Vertical variations in the feldspar content.


METRES
2 PERCENTAGE OF CLAY IN WHOLE SAMPLE
1 PERCENTAGE OF CLAY IN FRACTION LESS THAN 200 MESH
VERTICAL PROFILES IN PITS 3 AND 4
2 PIT 4
1 PIT 3
2 PIT 3
1 PIT 4
DEPTHIN FEET BELOW SURFACE
METRES
2 PERCENTAGE OF CLAY IN WHOLE SAMPLE
1 PERCENTAGE OF CLAY IN FRACTION LESS THAN 200 MESH
VERTICAL PROFILE AT END OF TRENCH
DEPTH IN FEET BELOW SURFACE

TEXT-FIG. 10.—Vertical variations in the clay content.

70 per cent by volume 10 cubic feet of original rock will be expected to give about 3·3 cubic feet of compacted Zone I debris.

(*d*) *The Role of Sub-Surface Water*

The surface mantle is most permeable on the hillslope where gravelly Zone III outcrops. Downslope, owing to a decreasing content of gravel and increasing content of clay, vertical percolation after rain must become steadily less, despite the decrease of slope. After intense rain much water will flow over and through the debris on the hillslope and some may enter the weathering profile on the pediment easily at or just above the piedmont angle. From here on it is confined between the practically impermeable bedrock and the decreasingly permeable surface clayey layer. As it nears the poorly permeable compacted debris the rate of flow will slow down and the water level will rise until an escape outlet is found to the surface. Thus the seepage line will be expected to occur at the upslope limit of the zone of compaction.

After every big storm a powerful flushing of water through the weathering profile on the upper pediment slope is to be expected. Stagnant water, bearing a few gases and a high content of solutes, is replaced by fresh water charged with gas, and intense chemical weathering is expected accordingly. From an inspection of Text-fig. 3c and Table III it is immediately apparent that the greatest weathering, leaching, and eluviation has occurred below the wet season water-table when it would be raised high enough for seepage to occur at the seepage line.

It is well known that feldspars weather to clay along their cleavage planes. If the clay so formed is not removed (and provided it is not an "acid clay") then it is believed that the kernels of fresh feldspar sheathed in clay are partly protected from further attack (see Nye, 1954/55, where much feldspar persists in the sand fraction throughout his profile and where lateral flow and lateral eluviation are not in evidence). It is doubtful if vertical percolation is ever strong enough to cause vigorous mechanical eluviation except down root channels. But lateral flow along and just below the high wet season water-table would be strong enough to displace and remove clay size particles from the weathering feldspar, and so allow it to be continuously and vigorously attacked. Thus the zone of strongest flushing by lateral sub-surface water flow is also the zone of least orthoclase, least clay, most quartz, and most eluviation.

IV. The Course of Erosion

(*a*) *Migrationary Material*

The migrationary material at 6 inches depth in the trench is roughly comparable in feldspar content and grade size distribution to the Zone

II–III debris from 5 to 6 feet depth. This is presumably because it has been derived from similar debris on the hillslope either by rain and rill wash or by creep or both. From the base to the top of the migrationary zone the pit samples show a marked increase in feldspar and clay content with a sharp decrease in gravel. Averages of all the migrationary zone samples show that the debris only represents a maximum of 43 per cent by volume of the original rock.

The quartz appears to have been considerably disintegrated by transport. A normal ratio of 5 parts of quartz gravel to 1 of quartz sand in the sedentary zone downslope from the trench becomes a ratio of 1 part of quartz gravel to 3 parts of quartz sand in the overlying surface samples. Part of this difference on the surface could be due to selective downslope wash of the smaller grains. But since there is no notable accumulation or concentration of quartz gravel on the surface upslope much of this change must be due to further disaggregation of the quartz.

(*b*) *Removal and Renewal*

Surface removal of soil and sub-surface renewal of the residual debris by a lowering of the basal surface constitutes one of the normal processes of ground lowering, and it implies a thin surface layer of migrating material. The concept of the "renewal of exposure", clearly outlined by Penck (1953, pp. 62–66), has been followed by Stheeman (1932) and Nye (1954/55). It is probably operative on the hillslope of Jebel Qasim which appears to be retreating parallel to itself.

The feldspar-rich layer of migrationary material on the pediment around Jebel Qasim could not have come from the feldspar-poor Zone I material below. It must have originated mostly from the hillslope. The decrease in feldspar contents beneath the surface could be due either to a mixing of the two zones at their junction or to the longer period of weathering which the lower layers have undergone or both.

The pediment around Jebel Qasim thus represents a surface of transportation for debris from the hillslope across its whole width, while in its upper part active sub-surface erosion is in progress as well.

(*c*) *Mechanical Eluviation and Washing Out*

Mechanical eluviation becomes an important agent of erosion if the particles displaced can exit at a free face. In this case the free face is the ground surface and seems to coincide with a narrow strip on the upslope side of the zone of compaction.

The fact that a thin patchy cover of clayey silt occurs just below the seepage line where washing out is expected suggests that part of this fine material has come from the sub-surface weathering profile by mechanical eluviation. If this is so then apart from selective washing of the clay from off the hillslope on to the clay plain there is also a

considerable contribution from beneath the upper pediment. Indeed if Pit 4 is representative of the state of the lower pediment debris then perhaps nearly one-third of the original rock has been converted into clay and washed on to the plain from the weathering profile. This is apart from the soluble and colloidal material washed out which may in part recombine to give other clay minerals further downslope.

(*d*) *Pediment Lowering*

In Pit 4, from 3 to 9½ feet the total loss by volume from the original rock is at least 65 per cent. Since this debris has a specific gravity of 2·4 (all three samples were measured) then 10 cubic feet of original rock would give just less than 4 cubic feet of compacted debris. Since this is a vertical contraction the residual debris will be less than one-half of the thickness of the original granite from which it was derived. If Pit 4 is representative of the lower pediment then a considerable amount of pediment lowering will have occurred as a result of sub-surface erosion alone.

After compaction the upper part of the sedentary zone will be resistant to erosion. If the veneer of migrationary material is removed sheet wash may cause a slow degradation. Observations on other hills show that the main agent of degradation on the lower pediment is gullying, usually along cracks in the debris. Any crack will represent a free face for further eluviation and will also serve to concentrate the rain wash. The gully will rapidly excavate down to the permeable and more friable Zone II–III debris near the basal surface. Then rapid erosion of this layer will undermine the more compact upper layers and much of the weathering profile may be rapidly stripped off. It is probable that once a gully course heads up into the moist incoherent zone differential erosion would remove this material more readily than that below and might thus give rise to a scarp foot depression.

Jebel Qasim was chosen for study because of the absence of gullies and no stream courses occur within two miles of it. So later erosional features have not received close attention.

V. Discussion

(*a*) *Mechanical Eluviation*

Mechanical eluviation or the movement of small-size particles through the interstices of larger ones by circulating water has been considered as an agent of sub-surface erosion by various workers.

In 1922 (p. 582) M. Y. Fuller suggested that local solution of the calcareous particles in the loess of China had increased its porosity sufficiently ". . . to permit mechanical transportation of the finer particles of the loess ". Later Rubey (1928, p. 421) claimed that the washing out of fine clay and silt particles from the subsoil of parts of the

Great Plains in the United States by percolation of water led to the formation of sub-surface tunnels followed by caving. This sub-surface erosion was greatest just below the temporary ground water level of the rainy season and the vertical scarps of the gullies were its surface manifestations. Confirmation of Rubey's deductions was suggested by Buckham and Cockfield as a result of study of a system of sinkholes and tunnels in the Pleistocene silts of British Columbia (1950).

From studies in south-western Uganda, Stheeman (1932, p. 8) found that most of his pits in the polymict layer on the pediments had only ½–1 gramme of cassiterite per cubic metre, but in the dry valleys 5 to 6 grammes per cubic metre occurred. He wrote: " The distribution and concentration of this fine cassiterite must be ascribed to the action of the ground water in transporting the smallest particles of the detritus along minute channels."

White (1949, pp. 177–178) from studies in Oahu, Hawaii, claimed that on the steep slopes, " The interstices in these [basic] volcanic rocks are continually being filled and flushed out with rain-water . . . As it passes through the soil, it carries some of the smaller particles of weathered rock with it." He suggested that although many particles are washed in, some emerge after a short distance leaving a deposit of reddish brown mud on the surface. An effective process of erosion thus operated beneath the plant network and " The forest is thereby lowered on to less decomposed bedrock ".

From studies in Hong Kong on granite, we (Ruxton and Berry, 1957) claimed that the removal of clay size particles (less than 0·005 mm.) from the sandy debris was taking place on a large scale in certain situations.

For active eluviation to occur there must be a considerable range in the grade size of the deposit, a powerful flow of sub-surface water, and available space into which the fine particles can move. In the moist incoherent debris on the upper pediment slope at Jebel Qasim all these conditions are fulfilled, the free face in this instance being the sandy ground surface thinly covered with short grass.

(b) Comparison with Ghana

Clayton (1956) described linear depressions around granitic inselbergs in the Shai Hills on the south-western corner of the Dahomey pediplain, Ghana. A scarp foot depression sometimes occurs just below the piedmont angle and finger-like gullies with zones of soil wash emanating from them occur downslope from it. He suggests that moisture is retained in the scarp-foot debris for longer periods of the year than elsewhere and so there is a zone of more thorough chemical weathering which ". . . might be a natural target for rejuvenation ". The soil wash pattern around Jebel Qasim is almost identical

in character with the pattern round the western scarp foot of the Shai Hills (Clayton, 1956, fig. 8, p. 109). The only difference is that Jebel Qasim has not yet been gullied; if it were then one would expect a similar pattern on rejuvenation to that in the Shai Hills. In both the Shai Hills of Ghana and in the east-central Sudan hill masses rise abruptly from clay plains with thin weathering profiles. A grass vegetation occurs on the fringing pediments and a savannah climate prevails. Perhaps a similar cycle of solution, mechanical eluviation, and compaction of the residual granitic debris is occurring on the upper pediment slopes in both areas.

(*c*) *Formation and Maintenance of Piedmont Angle*

The sudden break-up of granitic corestones and boulders below a certain diameter to arkosic gravel or sand means a sudden break in the mobility (the ease of removal by erosion) of the debris. If this break occurs at and near the surface down a gentle slope, selective erosion by unconcentrated wash will be expected to remove the finer grade sizes of the debris differentially and a slight break in slope will result. Then slightly more intense wash on the upper steeper slope may tend to give a thin protective veneer of migrationary material on the lower slope particularly just below the break in slope. Whether the surface is now being evened out by this deposition or not, sub-surface water moving downslope will tend to persist longer in places where the mantle of debris is thicker (or the basal surface deeper) than elsewhere, i.e. at, and just below, the break in slope. A continuation of selective surface erosion and differential sub-surface weathering will gradually accentuate this angle.

The differential weathering at this new " scarp foot " will produce more clay from the feldspar than is produced elsewhere. If the vegetation cover is not too thick upslope then lateral flushing of the sub-surface water after heavy rain will not only renew the supply of weathering gases but will also displace the protective coating of clay from around the feldspar grains and wash it through the sedentary zone. After a time the sedentary zone below the break in slope will tend to become progressively compacted or richer in clay. If the vegetation cover on the lower slope is thin enough and the surface debris coarse enough the water level will rise against the dense barrier on the lower slopes and seepage will occur at the ground surface. Thus a powerful free flow of sub-surface water can commence active washing out of the clay on to the surface. From now on both weathering and sub-surface flushing will be most concentrated just below the break in slope. The piedmont angle will be progressively more accentuated both by surface and sub-surface removal of debris and by rapid lowering of the basal surface.

Retreat of this newly formed pediment now takes place by " foot rot and collapse " at the piedmont angle concurrently with rapid erosion from the hillslope which now retreats parallel to itself. It may well be that once a sharp break in slope is formed the granite under the hillslope may unload parallel to it, thus to some extent assisting in a continuation of the parallel slope retreat. It is significant that so many straight hillslopes in this district have plane jointing parallel to them.

On the lower pediment slopes a layer of compacted debris is formed in the upper sedentary zone after complete decomposition and some eluviation. This stable mantle on a slope of 1 in 50 moves upslope as the hillslope retreats, and may later be further degraded by gullying.

It is this sudden contrast between the lower pediment with a slope of only about 1° and the steep hill slopes (20–30°), or even steeper isolated buttresses and domes, that characterizes granite inselbergs in savannah landscapes. Presumably less intense and less rapid weathering in more arid climates causes less accentuation of the piedmont angles and the pediments are therefore steeper. While the thick dense mantle of vegetation preventing exit of fine particles from the surface in wetter and more humid climates causes a thicker and more clayey mantle to form with no equivalent formation of a piedmont angle.

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Granite : Some Tectonic, Petrological, and Physico-Chemical Aspects

By Doris L. Reynolds

Abstract

Granites of the main movement-phase of an orogenic zone form an integral part of the tectonic pattern being characteristically located at the intersection of cross- and main-folds. Here, an older granitic core pierces upwards through the anticlinal vault to form a diapir-fold in which migmatization, synchronous with movement, leads to the evolution of granodiorite. At higher structural levels where pressure is lower K-granites occur. Only at sub-volcanic levels has evidence of melting been found.

Recent hydrothermal investigations, by Bowen and Tuttle, show that synthetic haplo-pitchstones which *begin* to crystallize at minimum temperatures become richer in K as pressure decreases. These results are closely comparable with evidence provided by the sub-volcanic K-microgranites (migmatized Caledonian granodiorite) of Slieve Gullion, but have no application to the granodiorites.

IN a recent series of interesting papers Professor Eskola has explained some changes in his views concerning the origin of granite and, as he expresses it, the concessions he has made since 1950 to the transformist views. In reading these papers I was surprised to realize that Eskola seems to think that transformists are not interested in the possibility of applying physico-chemical knowledge to the granite problem. As many published discussions show, this is far from being true. Transformists include specialists in many branches of our science, and it is a little unfair if it is to be supposed that Read was spokesman for them all when he wrote : " For my own part, I have to confess that I never did understand what many of the triangles meant ; I have, in fact, a great deal of sympathy with the Victorian statesman in the matter of those ' damned dots ' " (Read, 1951, p. 6 ; 1957, p. 345).

On the other hand I was even more astonished to discover, at an Inter-Collegiate Geological Congress held in Edinburgh last December, that I myself am supposed to think that granite is not intrusive. This is the more surprising because I was the first in the country to map (1934, Fig. 3, p. 594) the planar lineations in a granite mass (the Newry granodiorite), my object being to test the view held by some of my elders that the planar structures resulted from dynamo-metamorphism ; in fact, I found that they depicted flow. The map I refer to is incomplete, but it has to be remembered that it was made a quarter of a century ago, before the publication of Balk's (1937) book made Hans Cloos's methods easily available to the English-speaking world. At this early date I tacitly assumed that the granodiorite had moved as a melt or magma and, from the deflection of the adjoining

sediments, I inferred that the intrusion had exerted shouldering-stress. By 1949, however, having examined granites at a variety of structural levels, I realized that the intrusion of granite is " mainly a tectonic problem ; it is the problem of distortion and displacement of sedimentary masses in orogenic zones " (1949, p. 255). I agree with Eskola, " One must learn as long as one is living."

Since 1938, and particularly in more recent years, my published work has been mainly concerned with the evolution and movements of the Tertiary microgranites that occur in the upper part of and overlying the Newry granodiorite (Caledonian). In the course of this work I recognized that movement of granitic materials at a high structural level may result from fluidization (1951, 1954, 1955). It should perhaps be pointed out that fluidization is an industrial term used to describe a well-known process in which a bed of solid particles is expanded by the through-flowage of gas ; in the expanded bed the particles show turbulent motion. The process of fluidization is a highly efficient mixing process and brings about maximum chemical reaction between gas and solid particles. In the geological counterpart of fluidization, the temperature is sometimes sufficiently high to cause melting.

Searching to explain the astonishing misunderstanding and misrepresentation of my own work, and that of some of my colleagues and friends, it has occurred to me that the explanation is perhaps to be found in the disadvantages that arise out of what T. C. Chamberlin (1897, 1931) described as " the method of multiple working hypotheses ".

The problem presented by granite is of so fundamental a kind that it inevitably gives rise to multiple investigations : tectonic, petrological, mineralogical, geophysical, and geochemical, and the results of research in all these fields have to be held in mind together with the multiple working hypotheses provisionally based upon them. Although this is undoubtedly the scientific method of procedure it has, as Chamberlin pointed out, some disadvantages. The most obvious of these is that " We cannot put into words more than a single line of thought at the same time ". Added to this is the present-day difficulty that original investigations, however complex and extensive they may be, are required to be written for publication in the same meagre number of words that are accorded to investigations of simple repetitive type. To a reader who has not read all the previous reports on the subject, a geologist who follows the method of multiple working hypotheses may appear to be constantly changing his mind, or even contradicting himself. If, moreover, this reader happens to be the Referee on whose judgment the publication of the paper depends, then an essential step in the evolution of ideas may remain unpublished.

In his Memoir on the Stavanger area, Norway, Goldschmidt (1921) provides a very simple illustration of the kind of difficulty that may arise in the practical application of the method of multiple working hypotheses. Goldschmidt had previously found, in the Oslo region (1911), that metamorphism in response to rising temperature had taken place without chemical change ; by applying the phase-rule he had been able to determine the possible associations of minerals that could crystallize in a rock of known bulk composition undergoing metamorphism. In the Stavanger area, however, metamorphism had proceeded with additions and subtractions of materials ; water, soda, and silica had been introduced, and later these were followed by potash.

Goldschmidt concluded his work on the Stavanger area by pointing out that geologists might now be inclined to inquire whether the results he had obtained in the Oslo area were correct and those he had obtained in the Stavanger area wrong, or vice versa. But this, he added, would be asking the wrong question ; it should rather be asked under what conditions does metamorphism *without* chemical change take place, and under what conditions does metamorphism *with* chemical change take place ? Goldschmidt was inclined to think that depth of burial was one of the controlling factors. In France, Goldschmidt's correctly formulated question has been fruitfully pursued, and Jung and Roques (1952) have been able to define more precisely the conditions under which these two at first seemingly opposed kinds of metamorphism are operative. In other quarters, however, the wrong question having been asked, although perhaps unconsciously, it has become orthodox to accept Goldschmidt's results for the Oslo area, and to ignore his results in the Stavanger area.

A little reflection along these lines has revealed to me that there may be geologists who similarly suppose (*a*) metamorphism with change of chemical composition culminating in granitization *and* (*b*) movement to be mutually exclusive phenomena. It may be, for example, when I have specifically recorded petrological evidence of metamorphism that some readers have drawn the unwarrantable inference that there has been no movement, and vice versa. A further complication is added because on the one hand Wegmann (1930) has discovered that granites of the main movement phases in orogenic zones move in the same way as diapirs of salt whilst, on the other hand, I have found evidence at a high structural level—the sub-volcanic level—that rocks of granitic composition may move as fluidized systems in some of which the particles are melted droplets. There may therefore be geologists who are asking whether diapirism is correct and fluidization wrong or vice versa ; whether flowage of solid rocks is correct and flowage of melts wrong, or vice versa.

We are all agreed that melt of granitic composition is formed at some

level within the earth's crust, because we have visual evidence of its eruption at the earth's surface. The geologist's task is to discover the *evidence* of melting and so to locate, without prejudice, the structural level at which it occurs.

Although it is not possible, in a brief paper, to recapitulate all the relevant evidence disclosed by a variety of techniques, yet it may perhaps help towards mutual understanding if I attempt, in summary form, to correlate on broad lines some of the tectonic, petrological, and physico-chemical aspects of the problem in the light of present-day knowledge.

Tectonic

From the earliest days of geological investigations it was observed that granite occurs in the cores of mountain-ranges where it is flanked by steeply dipping layers of gneiss and schist, overlain in turn by less steeply dipping layers of sedimentary rocks. Hutton (1795), however, was the first to realize that these large-scale structural relationships might indicate that granite had risen upwards and actively uparched the superincumbent strata. His subsequent discovery that strata overlying granite on the north-west side of Glen Tilt are not only uparched but to some extent disoriented, seemed to confirm his hypothesis that granite had been melted deep-down in the earth with the result that it expanded forcefully upwards.

In 1803 von Buch independently came to a similar conclusion after observing that the mantling rocks were uparched around granite in the north-western Alps. He inferred that granite-melt, unable to escape to the surface, had forcefully uplifted the superincumbent rocks. In Switzerland, von Buch's hypothesis was generally accepted right up to the latter part of the last century when it was abandoned because Heim discovered that the very granites to which the melting hypothesis had been applied were of Hercynian age, and older than the rocks they were reputed to have uplifted. The structural evidence remained, however, and it was eventually recognized that these granites had moved passively upwards at the time of the Alpine folding, and thereby uparched the overlying strata. The importance of this discovery was that it led Argand (1916) to recognize that it was possible to decipher the movements of unexposed crystalline rocks from the movement-structures they had imprinted on the overlying and contemporaneously folded geosynclinal rocks. Movements of two structural levels of the earth's crust were recognized to be contemporaneous and disharmonic.

Following other lines of evidence, Michel Lévy (1888) discovered that metamorphism, at deep levels of the earth's crust, was accompanied by change of chemical composition and that the rocks at a low structural level were granitized. With the aid of many chemical analyses, meta-

morphism of this kind was eventually confirmed by Goldschmidt (1921) in the Stavanger area, Norway.

In Finland, a further discovery of fundamental importance was made. Sederholm (1907) observed that an old grey gneissic granite, intersected by a swarm of metabasalt dykes, had been granitized and at the same time had acquired ability to flow. As flowage-folds developed the metabasalt-dykes became intersected by cross-fractures, and the fragments thus formed became separated. Sederholm coined the term migmatite to describe incompletely granitized rocks with a mixed appearance.

In 1928 Wegmann, a student of Argand's who was already familiar with large-scale disharmonic movements of the two levels in Switzerland and the meaning of medium-scale movement-structures, was invited to Finland to investigate the granitized rocks and their environs. By determining the direction of fold-axes and analysing the movement-traces (commonly superposed) he established that flowage and concomitant granitization had taken place without disorganization of the older rock-framework such as would have resulted from widespread melting. The granitized rocks showed fold-forms similar to those already known in schists and sedimentary rocks, but of more fluid style ; the separated fragments of metabasalt (ladder-veins and boudinage) depicted the direction of extension-movements. Wegmann reached the conclusion that the granitized rocks, like salt-domes, had flowed relatively upwards in the cores of the anticlinal folds.

In 1910 Mrazec, working in the foothills of the Carpathians, coined the term diapir (through-piercing) to describe anticlinal folds in which the underlying older rocks (e.g. salt) pierce upwards through the vault of the anticline. Mrazec observed that the beds of the core of a diapir dip steeply whilst the overlying younger beds dip more and more gently away from the core, being arranged like the tiles on a roof as a result of relative down-gliding over the rising core.

Wegmann (1930) used the term diapir to describe similar piercement-folds where the core of an anticline, undergoing granitization, had moved relatively upwards and, like salt, had pierced the anticlinal arch. As a diapir rises, rocks which at a low structural level are obvious migmatites become more and more homogenized by the mechanical kneading caused by superposed movements (Wegmann), and by chemical interchange (with appropriate additions and subtractions) and recrystallization. In this way a migmatite rising in diapir style becomes gradually transformed to nebulite (Sederholm) and eventually to homogeneous granite. If recrystallization outlasts the movement then, just as in salt-diapirs, all traces of the movements may be lost.

In Greenland, where the rocks are magnificently exposed along the fjord walls, Wegmann (1935*a*) subsequently saw that during the

Caledonian orogeny, both the old crystalline rocks and a low structural level of the Caledonian geosynclinal rocks themselves became migmatized and rose as diapirs. The migmatites which become mobile and move upwards, Wegmann (1935*b*) termed the Infrastructure. The term Superstructure, on the other hand, denotes the highest structural level, i.e. the level unaffected by migmatization ; the rocks of this zone move obliquely downwards—as glide-folds—away from the rising Infrastructure. The zone of décollement (detachment) between the disharmonically moving Infrastructure and Superstructure, Wegmann termed the Transition zone ; it is the zone of regional metamorphism. The structural relationships are, however, much more complex than this brief statement would suggest, because the actual spacial positions of the three structural levels not only cross-cut the stratigraphy but vary with time, since they are controlled by the rise and fall of the migmatite front.

At the present time, when it is becoming more and more widely recognized that rocks may move by down-gliding under the influence of gravity, Haarmann's (1930) distinction between primary and secondary tectonics may be advantageously recalled. In the early part of this century it had become customary to divide crustal movements into radial and tangential movements relative to the earth's surface. Argand, recognizing that movement was three-dimensional, realized that radial and tangential movements took place concomitantly, but he thought that they resulted from tangential push. In 1930, however, Haarmann reinstated upward-movements in their own right as *primary* tectonics ; the uprise of geotumours. *Secondary tectonics*, according to Haarmann, were the resultant down-glidings from the rising geotumours.

Wegmann discovered that the immediate and investigatable cause of Haarmann's primary tectonics was the upward movement of Infrastructure within the axial cores of orogenic belts. He also discovered the meaning of cross-folds (1935*b*). Cross-folds result from the relatively greater upward movement of old granites and granite-gneisses in comparison with the other rocks in the rising Infrastructure. The Infrastructure, although undergoing migmatization, retains the trends of the older orogenic belt from which it is largely formed, and the old granites and granite-gneisses naturally conform with these trends. Their uprise, and consequent uparching of the Transition zone and Superstructure, therefore imprints these old trends upon the rocks of these higher structural levels. These uparchings, transverse to the main orogenic trend, form the cross-folds with their attendant down-glidings. Through the uparchings in the main and cross directions and the related down-glidings, the Superstructure and Transition zones become criss-crossed with superposed movement-traces.

These discoveries of Wegmann's were first made in Greenland

where they have recently been amply confirmed by Haller (1953, 1955). The granite problem is a tectonic problem and the granites form an integral part of the tectonic patterns. When viewed in this way the reason for the common location of granite diapirs at the intersection of cross and main folds (culminations of the Superstructure) becomes apparent. Magnificent examples of this relationship are provided by Eskola's (1949, 1952) mantled gneiss domes, which mark the intersection of the old Svecofennian trend (cross-folds) with that of the younger Karelian zone. The correlation between the location of granite diapirs and tectonic structures would be unintelligible if the granites resulted from the crystallization of melt derived either by crystal-differentiation of basaltic magma or by differential melting of deep levels.

If, unable to appreciate the strength of the tectonic evidence, there are readers who still suppose rock-flowage to be impossible, they should refer to King Hubbert's (1937, 1945) discussions of true to scale models. By reference to easily understandable analogies, King Hubbert demonstrates that " without the necessity of any special hypotheses of strength much less than, or of fluidity much greater than, that of the crystalline rocks of the earth's surface, the behaviour of the earth as a whole in geologic time must be very similar to that of the ordinary viscous fluids and extremely soft muds of our everday experience " (Hubbert, 1945, p. 1651).

The correlated disharmonic movements between Infrastructure or granite diapirs and their mantling rocks can now be recognized and interpreted by reference to the work of Wegmann, Fourmarier (1956) and other European geologists. As granite rises in the anticlinal arches, the mantling rocks move downwards into the adjacent troughs, the movement-structures having different styles at different structural levels. It is, however, only where granite diapirs have reached the zone of fracture that *evidence* of melting and the birth of acid volcanic rocks has so far been found. Much evidence concerning this level has been recorded by French geologists (Roubault, 1934 ; Lapadu-Hargues, 1947, 1953, *et alia*). Highly spectacular relationships between the upper part of a granite diapir and the Vulcanogenic level have recently been recorded by Barbeau and Gèze (1957). Here, however, it is only possible to discuss the petrological evidence from the Slieve Gullion area in the light of recent physico-chemical evidence.

Petrological

From many lines of evidence, including both geological obervations and physico-chemical experiments, it was discovered, during the last century, that water was intimately concerned in the origin of granite ; and the term aqueo-igneous came into use. Here, it must suffice to

recall only one of these outstanding investigations, that of Sorby's (1858) on the infillings of cavities in rock-forming minerals. Having proved the liquid within cavities in vein-quartz and the quartz of granite to be water, commonly containing salts of potassium and sodium in solution, Sorby concluded, with respect to the origin of granite. "The proof of the operation of water is quite as strong as of that of heat; and, in fact, I must admit, that in the case of coarse-grained, highly quartzose granites there is . . . very little evidence of igneous fusion, and . . . overwhelming proof of the action of water."

In recent years some of the most important work performed at the Geophysical Laboratory, Washington, has revealed that solids, e.g. orthoclase and albite, dissolve in gaseous water (Morey and Hesselgesser, 1951). Here then we have the possibility that the materials added to and subtracted from rocks undergoing granitization are transported through the *moving rock-framework* in aqueous solution, the solvent probably being in the supercritical state.

We are justified in thinking that at each structural level reaction will be directed towards the appropriate state of equilibrium between the solid and aqueous-fluid phases; reaction will proceed just as surely as if it were between early formed crystals and residual melt. As to what this equilibrium is, however, we can only discover from the geological evidence. The most characteristic granitic rock of the major intrusive masses of the early and main movement-phases in orogenic zones is granodiorite. At a later stage potash-granites (Backlund, 1943; Eskola, 1956) are the characteristic type, and have variously been classified as late-kinematic, post-kinematic, and katogenic. The point of importance, however, is that the potash-granites, at the time of their evolution, occupied a high structural level of the earth's crust relative to their granodiorite counterparts. In Britain, potash granites are well exemplified by the Tertiary microgranites and granophyres. In conclusion, then, it can be inferred that granodiorite is characteristically the stable type at low structural levels, where the pressure is high, potash granites, microgranites, and granophyres being the stable varieties at structural levels where the pressure is lower.

In addition to the potash-rich granites which, like the British Tertiary microgranites, occur at a high level in the Superstructure, there are potash-rich granitic rocks, located in the Transition zone, that form mantles or carapaces to the granodiorites of the main orogenic movement-phase. These may assume the form of augen-gneiss, in which augen of potash-feldspar replace composite augen composed of plagioclase and quartz (Backlund, 1950); examples are provided by the *embréchites* described by Roques (1941) from the Montagne Noire region in the Massif Central, France. They may also assume the form of granites with large crystals of potash-feldspar of late formation.

Although it is not possible here to discuss the potash-rich granites that characterstically form carapaces around granodiorites of the main movement-phase, it should be said that the known structural and textural evidence indicates that in these rocks the potash-feldspars—whether they appear as augen or as well-shaped crystals—have formed as replacements of relatively still spots in the movement patterns, that is at spots where pressure is relatively low. These granites are, therefore, in no way exceptions to what is now to be said.

Potash-metasomatism and Enrichment in Potash with Melting. At the International Geological Congress held in London in 1948, Eskola interpreted the potash granites, including granophyres, that characterize high structural levels in Finland, as ideal magmatic granites. At the same meeting, in describing identical rocks from the Slieve Gullion area, N. Ireland, I, on the other hand, showed lantern-slides illustrating the spectacular evidence that some of the Tertiary granophyres are here pseudomorphic replacements of the Caledonian (Newry) granodiorite, and have resulted from potash metasomatism (Reynolds, 1937, 1950). I shall always remember with pleasure Professor Esper S. Larsen's generous response on this occasion when he said " I am a magmatist but I am convinced ". It is now very gratifying to find that what Professor Eskola describes as his concession to the transformists concerns rocks of this kind.

Eskola now recognizes the potash-granites and granophyres, which he previously classified as ideal magmatic granites (1950), to be metasomatic replacements of more sodic varieties of granite. He seems not to realize, however, that like myself he has now found granitization in what according to Read is the " wrong geological setting ". It is important to keep in mind, however, when observed evidence is found to disagree with a man-made classification, that it is the classification that requires revision ; well-observed evidence remains for all time.

In the light of recent experimental evidence that feldspars dissolve in gaseous water Eskola suggests that the potash metasomatism has resulted from reaction between aqueous solutions and crystalline rocks ; I am in complete agreement with him on this point. Eskola regards the aqueous solutions, however, as being of hydrothermal and possibly pneumatolytic origin ; solutions that remained as residuals after the crystallization of more sodic granite magma. These solutions, according to Eskola, may granitize either a more sodic granite from which they were supposedly derived, or they may granitize other rocks of independent origin ; Eskola has, in fact, inverted Read's classification.

In the Slieve Gullion area Eskola's suggestion that the aqueous solutions are residual solutions is untenable. The granodiorite that is metasomatically transformed to Tertiary granophyre is of Caledonian age. It would certainly be a great difficulty to suppose that hydrothermal

solutions, remaining as a last fluid residuum after the crystallization of granodiorite melt in Caledonian times, were still available in Tertiary times, about 300 million years later, to bring about the metasomatic transformation. On the other hand, it cannot be supposed that the aqueous solutions remained as residual solutions after the crystallization, in depth, of an independent Tertiary granophyre magma ; the gravity measurements of Cook and Murphy (1952) show the Slieve Gullion area to be a gravity high. That the aqueous solutions were not derived from basaltic magma that underlay the area will become apparent later in this paper (pp. 392–3).

In the Slieve Gullion area there is evidence that the potash metasomatism culminated in the actual melting of the chemically altered rocks. At several localities narrow parallel-sided rims of potash-granophyre or -felsite have formed around each quartz group within Caledonian granodiorite. The formation of these rims involved addition of potash (Reynolds, 1937, 1941, 1950), and where the rims are of felsite melting can be inferred to have taken place. Similar evidence is provided by occasional rheomorphic veins that extend into dolerite from metasomatically transformed Caledonian granodiorite (Reynolds, 1937). There has also been melting, combined with enrichment in potash and silica, on a more extensive scale at a lower and unexposed level within the Caledonian granodiorite. This can be inferred from field and petrographic evidence relating to some of the intrusive microgranites, which I have designated transgressive granophyres (Reynolds, 1951, 1952). These microgranites, whilst being petrographically and chemically related to the granophyres of metasomatic origin (Reynolds, 1951, Fig. 3, p. 107), intrude through these layered granophyres and the associated layers of dolerite. Moreover, they sometimes contain inclusions of the underlying Caledonian granodiorite or of crystals of oscillatory zoned plagioclase derived from it. It is of paramount importance to emphasize the fact that intrusive microgranites on Slieve Gullion can be seen to intersect the flow-structure of the dolerites. This fact alone is sufficient to refute the suggestion of Wager and Bailey, Bailey and McCallien, and Elwell that the microgranites were intruded before the dolerites crystallized. Furthermore, veins of microgranite can be seen to intersect one another.

The cause of the melting of microgranite is a difficult and far from solved problem. The recent experimental work at the Geophysical Laboratory, as we shall see directly, provides evidence of some of the necessary conditions. It is the rise of temperature that is most difficult to explain. That the intrusion and extrusion of basaltic magma was partly responsible is abundantly evident, as I discovered in 1937 and 1941. That some further process was involved, however, is evidenced by the fact that dolerite has itself been locally melted where it adjoins

some of the intrusions of transgressive granophyre (Reynolds, 1951, 1952). This evidence is not necessarily to be interpreted as showing that it was granophyre magma that caused the melting. The recent experimental work, now to be described, supports my suggestion that gaseous water was instrumental in melting and dissolving the materials from which the transgressive granophyres crystallized. It may well have been the gas that had the high temperature, and this in turn may indicate that the gas was of deap-seated juvenile origin capable of providing heat by exo-thermic reactions at a high crustal level (Fenner, 1950). Since it may, in fact, have been some other and still unknown process that caused the rise of temperature let us avoid assumptions and " either . . . or " arguments.

Physico-chemical

Hydrothermal Synthesis. Within recent years, Bowen and Tuttle (1951, 1952, 1953) carried out some important experimental investigations, using pressures of gaseous water ranging from 500 to 4,000 atmospheres, in order to determine the temperatures at which crystallization begins in synthetic mixtures corresponding chemically to mixtures of albite, orthoclase, quartz, and water. In the brief reports of this work that have so far been published, the part of this system that corresponds chemically to simplified acid rocks has been described as " synthetic granite " (Bowen and Tuttle, 1951, 1952). This name is unfortunately very misleading because the recorded data relate only to the temperatures at which finely powdered homogeneous glasses begin to crystallize. If similar data were derived from investigations of natural rocks then the rocks themselves would be called pitchstones or obsidians, and the first signs of change from the glassy to the crystalline state would be described as the beginning of devitrification. For brevity and greater accuracy let us therefore refer to the chemical systems as haplo-pitchstones.

The chemical systems so investigated by Bowen and Tuttle are highly complex. These systems include : (1) haplo-pitchstone in which water is gradually dissolved in increasing amount with increased pressure and temperature ; (2) gaseous water in which constituents of the haplo-pitchstone become differentially dissolved ; and (3) the first minute crystals that form in the hydrated haplo-pitchstone when, after weeks or months have elapsed (Tuttle, 1955, p. 301), equilibrium is thought to have been attained.

Striving to convey the complexities of hydrothermal synthesis to specialists in other branches of science, Morey (1953) has written : " Even in so simple a system as $H_2O-Na_2O-SiO_2$ the complications become formidable and necessitate consideration of four-dimensional space . . . With more components the difficulties become so great that

I cannot see how we can either plan our work intelligently or talk to anybody else about it. The limitations are not with our hands but with our brains."

Erroneous impressions conveyed by diagrams illustrating Hydrothermal Synthesis. In order to express their experimental results in a simplified form Bowen and Tuttle have projected the temperature contours of the liquidus (beginning of crystallization of glass) surface, for stated pressures of H_2O, on to a water-free plane. The resulting diagram is a triangular diagram in which the corners represent 100 per cent SiO_2, Ab, and Or respectively. These diagrams represent and correlate only two varieties of data ; (*a*) the normative compositions of the original water-free chemical mixtures and (*b*) the temperatures at which the corresponding haplo-pitchstones *begin* to crystallize. The chemical composition, expressed as normative quartz, albite, and orthoclase, of the haplo-pitchstone that begins to crystallize at the lowest temperature, for the particular pressure of gaseous water concerned, is coincident on the diagram with the point indicating the minimum temperature ; Tuttle (1955, p. 300) has described this point as a " thermal abyss ".

The simple appearance of such normative diagrams combined with the use of expressions such as " thermal abyss " and " minimum temperature " tends to lead a reader to suppose that the chemical composition corresponding to the minimum temperature is a eutectic composition. Arising out of such a subconscious influence, geologists of high repute have already referred to the lowest temperature at which crystallization begins as the " ternary minimum " or " granite minimum ", and to the composition of the corresponding haplo-pitchstone as the " eutectic composition ", the " granitic eutectic " or the " eutectoid ".

When a eutectic body solidifies the component minerals crystallize together, crystallization beginning and ending at the same temperature. Nothing that has been published by Bowen and Tuttle, or by Tuttle alone, indicates that a haplo-pitchstone has been completely or even mainly crystallized ; published data relate only to the temperature of *beginning* of crystallization. We have not yet been told whether this temperature has been determined experimentally, or whether it has only been inferred from the point of possible intersection of experimentally determined curves. Nor has any statement been published to indicate what it is that begins to crystallize. Indeed Wyart's (1955) experimental crystallization of obsidian from the Lipari Isles, in the presence of gaseous water with various salts in solution, under pressure, revealed that feldspar crystallized before quartz. By way of explanation it should be pointed out that the grain-size of crystals resulting from hydrothermal synthesis is commonly so minute that the minerals can

only be recognized by using X-ray techniques. Wyart (1955) was exceptionally successful in crystallizing obsidian with a grain-size so coarse that it resembled rhyolite.

When Frederick Guthrie (1884) first discovered eutectics he recognized that bodies he had previously termed cryohydrates were but varieties of eutectics. Cryohydrates were eutectics derived from the solidification of aqueous systems. Guthrie found that eutectic bodies, solidified from aqueo-igneous systems, solidified at temperatures lower than that of the melting point of ice. In the hydrous systems investigated by Bowen and Tuttle water becomes dissolved in the glass or melt, and the amount of dissolved water increases as the pressure increases (Bowen and Tuttle, 1951, p. 38). Just as in the case of the aqueo-igneous systems investigated by Guthrie at atmospheric pressure, the temperature of beginning of crystallization of a haplo-pitchstone decreases as the amount of water dissolved in it increases. Bowen and Tuttle's experiments differ from Guthrie's principally in the fact that high pressure is necessary to increase the amount of water dissolved in their haplo-pitchstones, and it is out of this factor that the much greater complexity of the systems arises.

The term "eutectoid", adopted by Eskola to describe bodies corresponding chemically with the lowest temperature at which crystallization begins, is also, as he points out, not really appropriate. A eutectoid resembles a eutectic except that it is crystallized from another solid instead of from a liquid.

To avoid inaccuracy, and for brevity, let us coin a new term. In the series of possible haplo-pitchstones, let us call the haplo-pitchstone that *begins* to crystallize at the lowest temperature for a given pressure a *minimite*. The term minimite carries no implication that the body to which it applies was ever completely or largely crystallized, or that it could be completely crystallized. The information as to whether a minimite can be crystallized completely at a fixed temperature or through a temperature interval is still awaited.

An Important Experimental Discovery. In the course of their experimental investigations Bowen and Tuttle (Bowen, 1954) made a discovery that has an important, and previously unrecognized, petrological application. They found that the composition of the minimite varies with the pressure of gaseous water, and that the temperature of beginning of crystallization shows a corresponding variation. The compositions of minimites corresponding to pressures ranging from 4,000 to 500 atmospheres are shown on the normative diagram, Text-fig. 1; the minimites become progressively richer in Or and Q as the pressure decreases. There is a corresponding progressive increase in the temperature of beginning of crystallization or, inversely, of completion of melting (Tuttle, 1955, Fig. 4, p. 302). On

Text-fig. 1 a relevant curve indicating the direction of fractionation is drawn in freehand, for 1,000 bars pressure of H_2O, from Tuttle's (1955, Fig. 5) diagram showing the curves of fractionation in the system. The curves of fractionation intersect the line joining the minimite compositions corresponding to various pressures, and these two directions can therefore be easily distinguished.

Comparison of Natural Granites with the Experimental Results

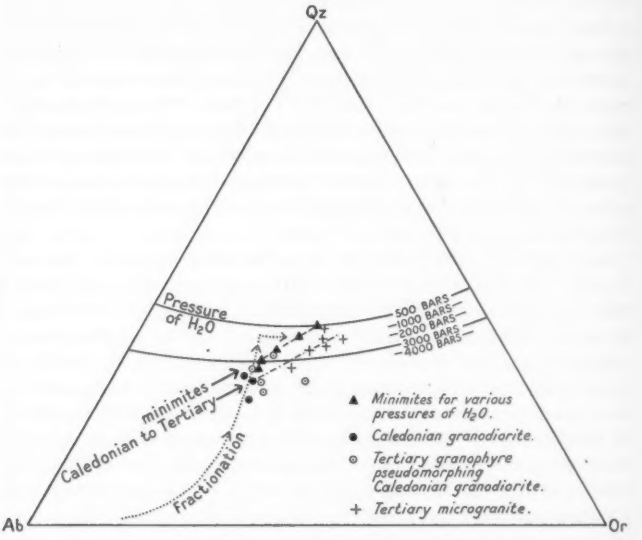
On a normative diagram similar to that on which the experimental data are depicted, Tuttle (1955, Fig. 7, p. 304) has plotted 571 granites, taken from Washington's Tables, in which normative Q + Ab + Or constitute 80 per cent or more of the norm. The correspondence between the area within which these rocks fall and the positions of the experimentally determined minimite compositions at various pressures is regarded by Tuttle as evidence that granites have crystallized from melts and, furthermore, as evidence that transformists will not be able to explain in any other way.

Lack of Agreement between Experimental Data and Low-level Granites. Barth (1955) and Perrin (1957) have already discussed Tuttle's inference with respect to the compositions of granites of their own countries. Both of them make it clear that in selecting granites containing 80 per cent or more of normative Q + Ab + Or Tuttle has omitted the most common granites of orogenic zones ; he has omitted the granodiorites and related types. Barth has emphasized this omission by plotting all the granites and gneissic granites of southern Norway on a similar diagram. Only the relatively high-level granites fall within the area that Tuttle regards as being appropriate to magmatic granites. All the others show " a nearly perfect dispersal without any relation to the critical line " (Barth, 1955, p. 123) ; the critical line being that joining the minimite compositions for various pressures as shown on Text-fig. 1. Eskola (1955) has similarly plotted 149 Finnish granites on the normative Q + Ab + Or diagram ; here again there is a wide dispersal of points representing natural granites. There is, however, a concentration of points representing high-level potash-granites on the orthoclase side of the critical line.

From Barth's, Eskola's, and Perrin's diagrams it is apparent that the dispersal of the points representing the granodiorites and related rocks of the main movement phases is incompatible with these rocks having resulted from crystallization (1) of residual liquids arising from the crystal differentiation of basalts ; or (2) of liquids derived by the partial melting of basalts ; or (3) by reference to the " critical line " joining the minimite compositions, of liquids derived by melting at various pressures. The experimental evidence is in agreement with the tectonic evidence and, as indicated earlier, the tectonic evidence shows

the granites to be an integral part of the tectonic structure of the continental crust.

Application of Experimental Evidence to High-level Potash-granites. It now remains to show that Bowen and Tuttle's experimental evidence has an important application to the potash microgranites formed from Caledonian granodiorite, at a high structural level, at Slieve Gullion.



TEXT-FIG 1.—For explanation see text pages 390–1 and 392.

Ten chemical analyses of these Tertiary microgranites, together with three chemical analyses of the Caledonian granodiorite from which they were derived, are plotted on Text-fig. 1. The parallelism between the line of microgranites and the line joining the minimite compositions at different pressures is very striking. Like Eskola's high-level potash-granites, the Tertiary microgranites certainly lie nearer to the Or corner of the triangle than does the line joining the minimites, but the discrepancy is no more than would be reasonably expected when natural phenomena are compared with laboratory experiments.

The line of Slieve Gullion microgranites makes a high angle with the curves of fractionation (Tuttle, 1955, Fig. 5), one of which is shown on Text-fig. 1. It can therefore be concluded, by reference to the experimental evidence alone, that the Slieve Gullion microgranites did not

result from (1) crystal fractionation of basaltic magma ; (2) fractional melting of basaltic magma ; or (3) fractional melting of Caledonian granodiorite. The trend of microgranites is, on the other hand, consistent with my inference from petrological and chemical data that these rocks were derived from Caledonian granodiorite by a process of enrichment of the latter in potash and silica.

The diagram, Text-fig. 1, does not in itself provide evidence that there has been melting ; such evidence can only be discovered, as it has been for some of the transgressive microgranites, from field and petrographic evidence. It is, however, very gratifying to me that the experimental data match the evidence of my rocks so exactly that they confirm my inference, of eleven years ago, that " If the temperature and pressure conditions, etc., are appropriate, fusion of the transformed rock will naturally take place " (Reynolds, 1947). As a direct result of the experimental investigations of Bowen and Tuttle, the presence of gaseous water can now be specified as part of the " etc." in the above quotation.

The experimental results also confirm the field evidence that the microgranites that crystallized from melts did not come into being by a single act. Like the experimental minimites each individual member of the series could be formed only at a specific pressure. The experimental data further indicates that melts from which transgressive microgranites crystallized were viscous glasses at the temperatures and pressures concerned. Indeed Tuttle (1955, p. 301) has recorded that " the thermal abyss corresponds to a viscosity maximum ", only the orthoclase-quartz " eutectic " (or is it a minimite ?) is more viscous (Tuttle, 1955, p. 301).

Apart from the investigations carried out at the Geophysical Laboratory, there are results of experimental investigations of viscosities to guide us. Saucier (1951) has determined the viscosity of a retinite, chemically similar to the obsidian of the Lipari Isles, and found it to be 10^7 poises at 980° C. under a pressure of gaseous water of 750 bars. Furthermore, Sabatier (in Wyart, 1955) has determined the viscosity of obsidian under pressure of gaseous water at 750 bars and found it to be 5. 10^9 poises at a temperature of 750° C.

Glasses with such high viscosities could no more penetrate joint planes, where the microgranites commonly occur as narrow veins, than sealing-wax at room-temperature can flow into cracks. To account for the transgressive microgranites the aid of some such process as fluidization is obviously essential, just as it is in industry where it is e.g. used to fill cracks and crevices with paint and enamel. The main agent concerned in natural fluidization appears to be gaseous water and this, together with its associates, are necessary, as already indicated, to facilitate melting. Evidence of the efficacy of gas as an agent of

transport is provided by nuée ardentes, and by the widespread flows of ignimbrites.

Now we must end on the same note as that on which we began. " We cannot put into words more than a single line of thought at the same time." In the latter part of the above discussion attention has been focused on melting, and some readers may therefore think that *all* the transgressive microgranites have crystallized from glass or melt. Basalts, to the south of Slieve Gullion, where they form part of the ring-complex, are intersected by net-veins that so much resemble granophyre in their macroscopic appearance that I collected them as such ; in fact, these veins are composed of minute fragments, including Caledonian granodiorite. Associated with the pyroclasts in these veins are bipyramidal crystals of quartz. These narrow tuff veins can only have been emplaced as fluidized systems, and it is possible that the quartz crystals were sublimated from the gas. The possibility that some of the transgressive granophyres are metasomatic replacements of similar tuff veins should not be overlooked. It is also possible that the materials (quartz and feldspar) of veins that are no more than 2 or 3 mm wide may have crystallized from gaseous or hydrothermal solutions. Those who know Stravinsky's *Petrouchka* will understand. In music a variety of themes can be superposed and interwoven ; sentences, perforce, are linear.

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On the Occurrence of Ankerite in a Band of Non-marine Lamellibranchs from the Lancashire Coal Measures

By F. M. Broadhurst and R. A. Howie

(PLATE IX)

Abstract

The shell-substance of the non-marine lamellibranchs from a band in the Lower *similis-pulchra* Zone of Lancashire is shown to be ankerite. The same mineral also forms pockets inside certain of the shells, the pockets being developed most frequently in the stratigraphically uppermost part of the spaces between the valves. It is considered that the ankerite in the pockets has occupied spaces left by shrinkage of the original mud-filling of the shells. Chemical analyses, specific gravity, and optical properties of the ankerite are given ; its composition closely approximates to $(Mg_2Fe)Ca_3(CO_3)_6$.

Introduction

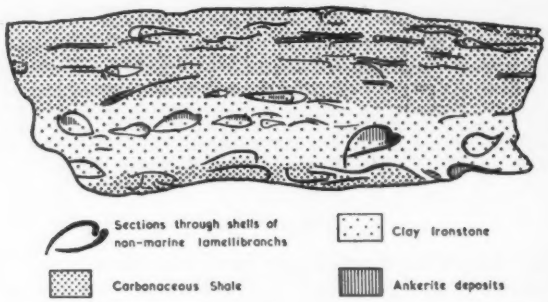
THE non-marine lamellibranch band, referred to in this paper, occurs about 30 feet above the Top Furnace Mine near the base of the *similis-pulchra* Zone in the Coal Measures of the Manchester area. The band was first described by W. B. Wright (1929) and later (Tonks *et al.*, 1931) it was labelled as Bed OC 8 at Oak Victoria Colliery, Oldham, where the present study has been carried out. The upper part of Bed OC 8, to be described elsewhere, consists of 30 inches of shale containing abundant *Anthraconaia*, with occasional *Anthracosia* towards the base. The lower part of Bed OC 8, 10 inches thick, is full of specimens of *Anthracosia* belonging to a number of species including *A. caledonica* and variants of *A. aquilina*, *A. ovum*, *A. fulva*, *A. lateralis*, and *A. simulans*. *Naiadites* also occurs. This *Anthracosia*-rich band is the subject of the present study.

The *Anthracosia*-rich Band, Distribution of Shells, and Petrology

The shells of the *Anthracosia*-rich band, in Bed OC 8, are not evenly distributed through the bed, but occur in courses within which the shells are frequently so tightly packed and crushed together that it is very difficult to extract or even fully expose the individual shells. About 7 inches above the base of the band there is a lenticular body in which shells are relatively uncommon and in which cone-in-cone structure has been developed. It is possible that the shells elsewhere in the band reinforced the sediment and there obstructed the formation of cone-in-cone structure.

The matrix between the shells of the *Anthracosia*-rich band is mostly

carbonaceous shale, the clay minerals being mainly illite with some kaolinite (we are indebted to Dr. Jack Zussman for these identifications which are based upon X-ray diffraction patterns). Elsewhere clay ironstone is developed in nodules or bands, and where it occurs the enclosed shells are preserved " solid " whereas the shells not preserved in clay ironstone matrix have been crushed by the weight of the overlying sediments. The clay ironstone formation must thus pre-date



TEXT-FIG. 1.—Semi-diagrammatic representation of a hand specimen, about 7 inches long, from the *Anthracosia*-rich band at the base of Bed OC 8, lower *similis-pulchra* Zone, Oak Victoria Colliery, Oldham, Lancashire. The shells preserved in carbonaceous shale are crushed, whilst those preserved in clay ironstone are uncrushed and contain pockets of ankerite generally just beneath the upper of the two valves.

compaction of the sediments and is probably contemporaneous or penecontemporaneous with the deposition of the sediments. The shells possess thick valves and since these constitute a relatively large proportion of the total volume of the rock it is not surprising that the *Anthracosia*-rich band and a similar band (referred to as OC 7 by Tonks *et al.*, 1931) about 16 feet below were formerly described as " *Carbonicola* limestones " (Tonks *et al.*, 1931, p. 39).

MINERALOGY

The yellow-white crystalline carbonate material found in the shell substance and in infillings between the shells has been investigated in detail. The carbonate of the shell substance is rather darker in colour possibly due to its frequently observed finer grain size. After preliminary break-up of hand specimens the carbonate was carefully handpicked: this material was then crushed to pass 100 mesh and further purified with heavy liquids to remove any remaining impurities. The results of two chemical analyses of this material are given in Table 1, together with the specific gravity and optical properties

and the recalculation of one analysis on the basis of 6 (0) atoms and in terms of the carbonate molecules. X-ray data on this mineral will be published elsewhere (Howie and Broadhurst, MS.).

The composition of the carbonate closely approximates to $(Mg_2Fe)Ca_3(CO_3)_6$, and following the nomenclature of Smythe and Dunham (1947) and of Hey (1955), it is termed ankerite (in the classification arbitrarily suggested by Palache *et al.*, 1951, it would, however, be called ferroan dolomite).[1] As has been reported for earlier analyses (Smythe and Dunham, 1947) calcium carbonate is present in excess

TABLE 1.—ANALYSES OF ANKERITES FROM A BAND OF NON-MARINE LAMELLIBRANCHS

	1.	*2.*		*1A.*		
SiO_2	0·15	insol.				
TiO_2	tr.	0·20				
Al_2O_3	0·28					
Fe_2O_3	0·10	0·08	Fe^{+3}	·002		
FeO	12·06	12·35	Fe^{+2}	·330		
MnO	0·77	0·74	Mn	·022	·980	2·006
MgO	12·85	12·33	Mg	·626		
CaO	29·23	29·60	Ca	1·024	1·026	
Na_2O	0·06	0·07	Na	·002		
K_2O	0·01	nil				
CO_2	44·70		CO_2	1·995		
H_2O-	0·02	0·02				
Total	100·23			Molecular %		
			$CaCO_3$	51·1		
			$MgCO_3$	31·2		
D	2·97		$FeCO_3$	16·6		
ϵ	1·515		$MnCO_3$	1·1		
ω	1·710					

Analyst: R. A. Howie

1. Light yellow ankerite forming shell substance, Bed OC 8, Oak Victoria Colliery, Oldham.
2. Light yellow ankerite mainly from interior of shells (same specimen as for analysis above).
1A. Analysis 1 recalculated on the basis of 6 (0).

of that required to satisfy the formula (Mg, Fe, Mn)$Ca(CO_3)_2$; this excess calcium presumably substitutes for magnesium, although in the dolomite-ankerite series the two ions are not structurally equivalent. Manganese together with iron replaces magnesium, while the small amount of ferric iron is probably due to minor oxidation (for cases of slight oxidation in " chalybite " mudstones see Dunham *in* Edwards and Stubblefield, 1947, p. 251). The small but consistent value for sodium indicates the ability of this ion to substitute for calcium.

[1] A previous occurrence of ankerite associated with fossils was noted by Frei (1948) who described this and other minerals found within ammonite chambers.

Previous analyses of ankerites of comparable composition are given in Table 2, two of them being from other Lancashire Coal Measure occurrences and a third from the Coal Measures of north-east England. In addition to the major elements, manganese is a relatively important constituent in these ankerites, the Mn/Fe ratio being considerably higher than the average for sediments. Manganese is normally in solution under non-oxidizing conditions in carbonated waters as

TABLE II.—OTHER ANALYSES OF ANKERITE

	A.	*B.*	*C.*	*D.*
$Al_2O_3 + Fe_2O_3$	0·56			
FeO	11·54	12·60	14·16	15·63
MnO	0·50	1·23	—	0·90
MgO	12·72	12·71	11·18	10·79
CaO	30·60	28·52	30·08	28·74
CO_2	44·10	44·72	44·58	44·42
	100·02	99·78	100·00	100·48
D	2·96	3·006		3·05
ϵ		1·520		
ω	1·709–1·717	1·711		

A. Vein ankerite in Middle Coal Measures sandstone, Easington Colliery, Co. Durham (Smythe and Dunham, 1947). Analyst: J. A. Smythe.

B. Ankerite, Bleka mines, Telemarken, Norway (Johansson, 1948). Analysis recalculated from carbonates.

C. Ankerite as white parting in coal, Hoo Cannel, Lancashire (Sinnatt, Grounds, and Bayley, 1921).

D. White ankerite in joints in coal, Collins Green Colliery, Newton-le-Willows, Lancashire (Crook, 1912). Analysis recalculated from carbonates.

manganese bicarbonate; manganese carbonate may then be precipitated when CO_2 is removed by bacteria or by oxidation. The tendency of manganese to become concentrated in the carbonate iron ores was also shown by Landergren (1948).

DISTRIBUTION OF ANKERITE IN INFILLINGS

When orientated specimens of the *Anthracosia*-rich band are examined it is found that the ankerite between the valves of the lamellibranchs frequently occurs as small pockets beneath the uppermost valves (Text-fig. 1 and Plate IX, figs. 1, 2). In most cases it is possible to find a thin selvedge of matrix still adhering to the surface of the shell immediately above the ankerite infilling (Text-fig. 1; Plate IX, figs. 1, 2). The interpretation of this observation is that when the shells were buried the cavities between the valves were completely filled with sediment (later transformed to clay ironstone) which subsequently shrank in volume to leave a space in the upper part of the infilling, this space being later occupied by ankerite. The ankerite may also occur in other positions (Text-fig. 1, on left) between opposite

valves and here, presumably, shrinkage in volume was associated with a crack taking up a random position. In some cases the ankerite in the infillings has incorporated fragments of matrix (Plate IX). The restriction of ankerite infillings to uncrushed specimens of *Anthracosia* suggests that compaction of the sediments had already taken place before the ankerite was formed. If this is the correct interpretation of the evidence then the ankerite of the infillings is later in date than the clay ironstone, and if all the ankerite is of the same age then it would follow that the transformation of the shell substance into ankerite also post-dates the formation of the clay ironstone. It is possible that the infillings were first composed of an iron carbonate which was later altered or replaced by ankerite. In the uncrushed *Anthracosia* the original shell substance (calcium carbonate) may have been altered to iron carbonate before alteration to ankerite took place. But in the crushed *Anthracosia* it is very unlikely that any iron carbonate was formed, since otherwise the shells would not have been crushed, and here ankerite presumably followed straight after calcium carbonate.

An interesting case to be compared with that described here is given by Craig (1954) who found that where pyrite did not completely fill the cavities within microfossils of the Top Hosie Shale it occurred only in the lower part of the cavities, the remaining space above being occupied by calcite. In this case presumably all the cavity within the fossil was available for occupation by iron sulphide, and not just the upper part of the cavity as described here. The restriction of mineral pockets to certain parts of infillings in fossils could prove of value stratigraphically in providing evidence as to which was the top and which the bottom of a fossiliferous band.

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EXPLANATION OF PLATE IX

FIG. 1.—Thin section (normal to bedding) through shells of *Anthracosia* and enclosed ankerite deposits. The section is orientated to show the younger sediments towards the top of the page. Note the selvage of matrix between the infilling and the uppermost valve in three of the specimens. Bed OC 8, near base *similis-pulchra* Zone, Oak Victoria Colliery, Oldham.

FIG. 2.—As for Fig. 1, but with an ankerite infilling in close contact with the uppermost valve.

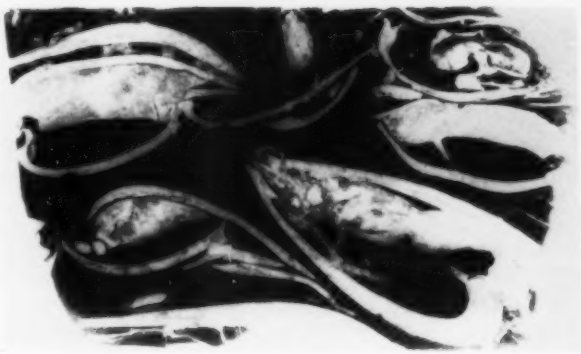


FIG. 1.

FIG. 2.

ONE INCH

ANKERITE IN NON-MARINE LAMELLIBRANCHS.

The Compositions of Coexisting Pyroxenes in Metamorphic Assemblages

By I. D. Muir and C. E. Tilley
with chemical analyses by J. H. Scoon

Abstract

Chemical and optical data are provided on pyroxene pairs in a range of metamorphic assemblages. Tie line trends in the system $CaSiO_3$–$MgSiO_3$–$FeSiO_3$ for these assemblages are compared with those recorded for plutonic igneous associations.

DATA on the composition of coexisting ortho- and clinopyroxenes in basic and intermediate plutonic igneous rocks have gradually been accumulating since Hess (1941) drew attention to the relationship of such pairs in his study on the pyroxenes of common mafic magmas. In this connection he noted that a tie line in the system $CaSiO_3$–$MgSiO_3$–$FeSiO_3$ joining compositions of coexisting augites and hypersthenes, if extended, intersected the $MgSiO_3$–$CaSiO_3$ side line at a position approximately $En_{55}Wo_{75}(Wo_{70-80})$. His data were largely drawn from the pyroxene associations of the layered intrusions of Skaergaard and Stillwater and he went so far as to suggest that the tie line relationship so defined formed a convenient basis for use to predict the composition of one pyroxene from a (plutonic) igneous rock, if the other pyroxene was known from chemical analysis or by determination from optical properties.

In terms of Mg-Fe partition in the pyroxene pair, this tie line relationship denoted a higher relative concentration of iron in the orthopyroxene member of the pair. It is to be noted that pyroxene pairs in phenocrystic volcanic rocks do not normally follow this relationship. In these assemblages there is a sequence of crystallization of the two pyroxenes with the phenocryst phase (e.g. hypersthene) relatively enriched in magnesia, a relation probably corresponding to non-equilibrium conditions.

Since Hess published his results further data have become available from plutonic assemblages, notably from the Skaergaard intrusion (Brown, 1957) confirming the relationship and indicating too that it applies where the coexisting lime-poor pyroxene is a pigeonite. Similar results have also been found to apply for the pyroxene pairs of the assemblages referred to the charnockitic series of Madras—in a group of rocks ranging from ultrabasic to intermediate and interpreted as metamorphic crystallizations (Howie, 1955).

In the course of an investigation of pyroxene relations in Hawaiian basalts the present authors described in some detail two examples of metamorphosed picrite basalts from Kilauea and compared the

TABLE 1A.—ANALYSES OF PYROXENE PAIRS FROM METAMORPHIC ASSEMBLAGES

	T	T¹	S	S¹	X	X¹	O	O¹	R	R¹
SiO_2	53·95	50·35	50·34	50·01	53·17	52·33	50·08	51·70	53·37	51·08
Al_2O_3	4·24	5·17	3·14	4·55	2·46	3·19	1·23	1·14	1·86	2·84
Fe_2O_3	2·24	1·69	2·97	2·61	0·91	2·22	2·34	1·00	1·61	2·41
FeO	8·40	3·28	22·53	8·07	13·06	7·85	27·85	12·30	12·96	5·78
MnO	0·25	0·13	0·70	0·29	0·28	0·21	0·85	0·41	0·43	0·28
MgO	30·17	15·41	19·52	12·40	24·74	18·16	15·78	12·00	27·33	16·11
CaO	0·57	22·80	0·60	20·82	4·19	14·85	1·44	20·82	1·85	20·31
Na_2O	0·03	0·44	0·05	0·70	0·18	0·53	0·05	0·21	0·08	0·37
K_2O	0·01	0·01	0·03	0·04	0·03	0·08	0·02	0·03	0·01	0·01
H_2O+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O-	nil	nil	0·03	0·02	nil	nil	nil	nil	0·03	nil
TiO_2	0·11	0·43	0·13	0·58	0·83	1·00	0·64	0·42	0·51	1·15
Cr_2O_3	0·05	0·12	—	—	0·06	0·08	—	—	nil	tr
	100·02	99·83	100·04	100·09	99·91	100·50	100·28	100·03	100·04	100·34

TABLE 1B.—FORMULA ON BASIS OF SIX OXYGENS

	T	T¹	S	S¹	X	X¹	O	O¹	R	R¹
Si	1·898	1·848	1·899	1·872	1·922	1·904	1·939	1·960	1·920	1·881
Al	0·102	0·152	0·101	0·128	0·078	0·096	0·056	0·040	0·080	0·119
Al	0·071	0·073	0·035	0·070	0·031	0·039	—	0·012	—	0·002
Ti	0·002	0·011	0·002	0·018	0·022	0·028	0·019	0·011	0·013	0·032
Cr	—	0·004	—	—	—	0·004	—	—	—	—
Fe^{III}	0·058	0·048	0·086	0·072	0·026	0·061	0·075	0·028	0·043	0·066
Fe^{II}	0·246	0·101	0·709	0·252	0·393	0·238	0·899	0·389	0·388	0·179
Mn	0·006	0·004	0·023	0·009	0·009	0·007	0·028	0·014	0·013	0·009
Mg	1·587	0·848	1·105	0·697	1·341	0·991	0·915	0·682	1·474	0·890
Ca	0·021	0·899	0·025	0·836	0·163	0·579	0·060	0·846	0·071	0·802
Na	—	0·031	0·004	0·049	0·013	0·035	0·004	0·014	0·004	0·022
K	—	—	—	—	—	0·004	—	—	—	—
z	2·000	2·000	2·000	2·000	2·000	2·000	1·995	2·000	2·000	2·000
x + y	1·991	2·019	1·989	2·003	1·998	1·986	1·990	1·996	2·006	2·004
Ca	1·1	47·3	1·3	44·8	8·4	30·9	3·1	43·2	3·6	41·2
Mg	82·7	44·6	56·8	37·4	69·4	52·8	46·5	34·8	74·1	45·8
ΣFe	16·2	8·1	41·9	17·8	22·2	16·3	50·4	22·0	22·3	13·0
$\frac{Fe}{Mg + Fe}$	0·16	0·15	0·42	0·32	0·24	0·23	0·52	0·39	0·23	0·22

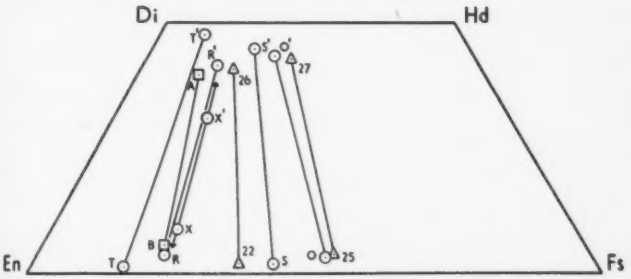
T–T¹ Olivine hypersthene pyroxenite, Scourie, Sutherland.
S–S¹ Hypersthene diopside plagioclase gneiss, Scourie, Sutherland.
X–X¹ Metamorphosed picrite basalt, ejected block Kilauea (Muir and Tilley, 1957, p. 242).
O–O¹ Hypersthene diopside plagioclase hornfels, Aarvold Quarry, Oslo district, Norway.
R–R¹ Olivine-bearing pyroxene granulite, Eilean Carrach, Ardnamurchan, Scotland.

All analyses by J. H. Scoon.

compositions of the pyroxenes derived from optic data in these assemblages with those determined by chemical analysis from the normal tholeiitic basalts. Comparisons were also made with assemblages in some other rocks of metamorphic origin where two pyroxenes were present. In all these metamorphic rocks the compositions of the pyroxenes were based on the optic data using the charts of Hess (1949) and Muir (1951), and the results of that study suggested that tie line trends for the coexisting pyroxenes departed significantly from those normally encountered in the igneous rocks (Muir and Tilley, 1957, fig. 3).

Subsequent work by Mr. M. J. O'Hara of Cambridge on some

metamorphic pyroxenic assemblages from Scourie, Sutherland, revealed that though some discrepant relations existed between the compositions of pyroxenes determined chemically and inferred from optical data—the actual tie line trend in the examples chemically studied did not depart significantly from that derived from the study of the plutonic igneous assemblages already noted. These results raised the question of the validity of determining tie line trends from purely optic data and indicated the need for further chemical study. This has now been carried out for the examples referred to in our earlier paper and the data are set out in the analytical and optical data of Tables 1A, 1B, 2, and Text-fig. 1.



TEXT-FIG. 1.—Compositions of co-existing pyroxenes in metamorphic assemblages. Tie lines of pyroxene pairs (orthopyroxene-clinopyroxene) from the metamorphic assemblages of Tables 1A and 1B, plotted in the system $CaSiO_3$(Wo)–$MgSiO_3$(En)–$FeSiO_3$(Fs). The tie line of the metamorphosed picrite basalt (XX') has been extended to indicate that the analysed pyroxenes X and X' were not wholly free from the respective associated pyroxene.

In addition tie lines 22–26, 25–27 show pyroxene pairs from two granulites of Lapland (Eskola, 1952, fig. 34). The tie line AB refers to an igneous assemblage—the " porphyritic gabbro " of Kilauea (Muir and Tilley, 1957, p. 244).

The results obtained show relatively good accord with the relation found in the igneous assemblages. The discrepant data of composition provided by optical properties are largely associated with the augite phase for which the optic plot is generally to the iron side of the position based on chemical analysis.

For the pyroxene X' of the metamorphosed picrite basalt and pyroxene R' of the Ardnamurchan granulite, this is doubtless in large part associated with the high TiO_2 values these pyroxenes show, though Fe_2O_3 is also in excess. On the other hand for the pyroxene O' of the Oslo district hornfels with relatively low content of minor constituents the agreement of optic with chemical data is good.

TABLE 2.—OPTICAL DATA AND

	T	T¹	S	S¹
α	—	1·686	1·701	1·694
β	1·683	1·691	—	1·700
γ	—	1·714	1·717	1·722
2V	− 84°	+ 55°	− 59°	+ 59°
Composition :				
From optics chart	Of_{17}	$Ca_{46}Mg_{39}Fe_{15}$	Of_{43}	$Ca_{46}Mg_{31}Fe_{23}$
From chemical data	$Ca_1Mg_{83}Fe_{16}$	$Ca_{47}Mg_{45}Fe_8$	$Ca_1Mg_{57}Fe_{42}$	$Ca_{44}Mg_{37}Fe_{19}$
Ex-solution lamellae	Sheets of pyroxene and iron ore rods in {100}	A few clinopyroxene lamellae in {001}, 2 sets of iron ore needles	A few pyroxene lamellae in {100}	Well developed pyroxene lamellae in {100} and needles of iron ore
Olivine	Fa_{11}		none	
Notes	Rock contains some hornblende, a little green spinel and biotite.		Rock contains a little biotite	

In view of the complexities introduced by minor constituents and the problem provided by exsolved phases (pyroxene or ore) for which a quantitative correction is difficult to assess, the use of the simple Ca : Mg : Fe ternary plot is likely to be inadequate generally to represent the optical properties of the more complex augites and certainly to call in question tie line trends based solely on optic data (cf., however, Brown's (1957, fig. 7) improved optic data curves for a specific group of clinopyroxenes—those of part of the Skaergaard gabbro layered intrusion).

In the orthopyroxenes optical anomalies are smaller and confined mostly to the size of the optic axial angle. In X where a notable titanium content in octahedral co-ordination occurs, the refractive indices have been noticeably raised, a feature which is in accord with the observations of Hori (1956) in his study of the effect of constituent cations on the refraction of orthopyroxenes.

The data now presented and summarized in the tables and diagram (Text-fig. 1) make clear then, that in metamorphic assemblages carrying two pyroxenes the tie line trends show no significant departure from that recorded from plutonic igneous assemblages.

OLIVINE-ORTHOPYROXENE ASSEMBLAGES

The relative magnesium enrichment (molfraction of magnesium

COMPOSITIONS OF PYROXENES OF TABLE I

X	X¹	O	O¹	R	R¹
— 1·694 1·699 − 63°	1·690 1·695 1·718 + 46°	1·707 — 1·722 − 50°	1·696 1·701 1·724 + 55°	1·680 — 1·692 − 69°	1·683–6 — 1·712–6 + 44°
Of_{37} $^{*}Ca_2Mg_{74}Fe_{22}$	$Ca_{22}Mg_{41}Fe_{31}$ $^{*}Ca_{21}Mg_{53}Fe_{14}$	Of_{44} $Ca_2Mg_{47}Fe_{50}$	$Ca_{43}Mg_{32}Fe_{25}$ $Ca_{43}Mg_{33}Fe_{23}$	Of_{32} $Ca_4Mg_{74}Fe_{22}$	$Ca_{28}Mg_{42}Fe_{19}$ $Ca_{41}Mg_{44}Fe_{15}$
none	none	none	none	none	Pigeonite and hypersthene in {001} and {100} respectively and two sets of magnetite lamellae
Fa_{10}		none		Fa_{27}	
* Probable compositions $Ca_2Mg_{74}Fe_{22}$ $Ca_{21}Mg_{65}Fe_{14}$		Rock contains some hornblende and biotite		Optics determined on grains devoid of iron ore	

silicate) of the olivine (C_o)-orthopyroxene (C_p) pairs of the assemblages represented in Text-fig. 1 are as follows:—

	C_o	C_p
TT' .	89	83½
AB. .	89	77½
RR' .	73	77
XX' .	81	73
4968 .	70	73

Included in this list are data from an olivine-bearing pyroxene granulite (4968) representing a recrystallized basalt lava in the aureole of the Cuillin gabbro, east of Sgurr na Stri, Skye. Of the five assemblages two only (RR' and 4968) show the olivine less magnesian than the associated pyroxene, the condition met with in the synthetic system MgO–FeO–SiO_2 (Bowen and Schairer, 1935). This is the relation then expected in such metamorphic assemblages which are completely recrystallized. The reverse condition, olivine magnesia enriched, shown in the remaining assemblages is doubtless a relation corresponding to a non-equilibrium state where a sequence of crystallization is involved.

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Note on the Structure and Microstructure of *Thecia swinderniana* (Goldf.)

By Jean G. Lafuste

(PLATE X)

Abstract

A study of thin sections of *Thecia swinderniana* (Goldfuss) shows the trabecular nature of the skeleton. It also appears that there are neither horizontal pores not vertical tubules in the walls, which are compact. A review of genera regarded by various authors as allied to *Thecia* leads the writer to retain in the family Theciidae only *Thecia* Edwards and Haime and *Angopora* Jones, the genus *Romingerella* Amsden being considered a synonym of the latter.

Introduction

THE genus *Thecia* was introduced in 1849 by Edwards and Haime; since then, to the characters given by these authors, various others have been added or substituted. It is for the purpose of throwing some light on the accurate constitution of the skeleton of this genus, from the point of view of the macrostructure and the microstructure, that specimens from the Silurian of Much Wenlock (Shropshire) have been studied with the help of numerous thin sections.

Macrostructure of Thecia swinderniana (Goldf.)

The superficial appearance of the colonies differs according to the state of preservation. The colonies from Much Wenlock, generally weathered or eroded, show calicular apertures reduced to 0·3–0·5 mm. in diameter, surrounded by rather short grooves, which vary in number but are commonly more than twelve. Some grooves are more marked than others and run from one calicular pit to a neighbouring one; these grooves are seldom straight, more commonly they are angled, each half being directed towards the centre of a corallite.

Colonies from Dudley [Collections of the British Museum (Nat. Hist.), and Coll. Munier-Chalmas, Laboratoire de Géologie de la Faculté des Sciences, Paris] are much better preserved: around the lumen, 12 main plates, radially directed, can be counted, with a number varying from 0 to 12 of shorter plates inserted among them. These plates are thin and their upper edge, which is subhorizontal, shows small irregular knobs. At the periphery of the calicles, variously directed plates may unite the external portions of the radial elements. This second kind of structure rapidly becomes in depth identical with the former by lateral thickening of the plates.

At the lower part of the colonies, which at Much Wenlock are generally more or less thick crusts, the walls of the corallites are thin (about 0·08–0·1 mm.); they become thick very rapidly towards the top, where they reach 0·5–0·7 mm.

From the main radial plates, spines project into the axial cavity, sometimes almost reaching the centre of the lumen.

The tabulae are thin, irregularly arranged, and often horizontal, but also convex or concave.

After this brief review of well-known characters, we may consider the more important question of pores in the midst of the walls.

Edwards and Haime, when they introduced the genus *Thecia* in 1849, noticed in their short description the presence of a compact false coenosteum. Nicholson (1879) figured the appearance, which we have already described, of weathered colonies with well-marked grooves uniting the adjacent corallites, and therefore reported the existence of pores in the form of horizontal channels. This opinion has been adopted, and attention has no longer been paid to the work of Edwards and Haime.

If such channels were present, then in a great number of longitudinal sections we should meet some horizontal interruptions in the closely united plates of the skeleton, but none have been encountered.

In thin longitudinal slides, small clear patches are observed in the walls, but that merely results from the undulating edges of the radial plates, so that the plane of the slides is sometimes in the cavity of the calicular chamber, which is filled with calcite clearer than that of the skeletal material.

Amsden, in 1949, described for the first time the " smaller vertical tubules, so tiny that eight or ten of them occupy a space of 1 mm." in the wall separating adjacent corallites of *Thecia minor* (= *T. swinderniana*). This opinion seems to have been accepted by some recent authors.

Bearing in mind the fact that the skeleton is built of thin lamellae which are thickened on their sides so as to become joined, it is difficult to conceive what may be the origin of such " tubules ".

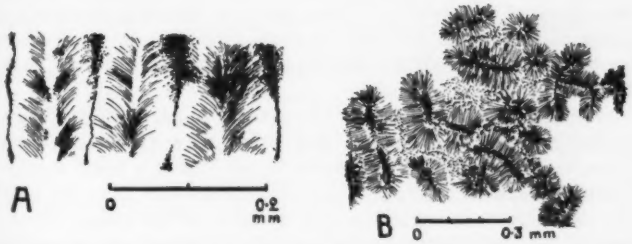
Microstructure of the Vertical Elements

Thin sections show several particularly well preserved areas where the microstructure is discernible.

The skeleton of *Thecia* is formed of calcite fibres directed upwards and outwards from the median axis or plane of each skeletal element. In transverse sections, these elements are more or less elongated : some are round and are the sections of rods, but the most numerous are sections of flattened plates. The median planes or axes from which the fibres diverge are often emphasized by an accumulation of dark material, generally arranged in irregular patches. But as is shown in Text-fig. 1, the black material is commonly concentrated at the external limits of the skeletal lamellae, the central zone of which then appears

clearer than the sides, the middle being furthermore occupied by whitish calcite. Whatever may be the distribution of the black material, the skeleton appears, in longitudinal sections, as built of parallel, alternating, clear and dark bands.

Examination of the photographs given by Amsden for *Thecia swinderniana* explains his belief in the existence of vertical tubules : between the calicular cavities, which are filled with clear calcite, the skeleton shows alternations of dark and whitish bands in longitudinal sections, and in tranverse sections minute clear patches embedded in darker matrix. On account of their similar appearance, he assumed the clear patches of the walls and the calcite filling the corallite chambers to be similar in origin.



TEXT-FIG. 1.—*Thecia swinderniana* (Goldf.). A, longitudinal section showing the concentration of the black matter at the exterior part of adjacent trabeculae ; B, transverse section of the wall between four corallite chambers.

The size given by Amsden for the so-called tubules, eight or ten in a space of 1 mm., agrees very well with the average thickness observed for the trabeculae of *Thecia swinderniana* from Wenlock and Dudley.

The growth of the upper part of the colonies of *Thecia* is produced by upward increase of the median part of the trabeculae. They become thickened laterally by lengthening of the calcitic fibres, and neighbouring trabeculae come into contact with one another. The superficial grooves described by Nicholson are the result of the slowness of growth of some trabecular plates.

REMARKS ON SOME GENERA BROUGHT NEAR *Thecia*

The classifications proposed for the Tabulata are still imperfect, and the genus *Thecia* is placed in very different positions in three recent systematic works :

Lecompte (1952) puts *Thecia*, with which *Angopora* is regarded as synonymous, in the family Columnoporidae, with *Columnopora*, *Fossopora* (sic), *Araeopora* and *Donetzites*.

Sokolov (1955), in the sub-order Favositina, divides the family Theciidae into two sub-families, Antherolitinae and Theciinae, the latter including the genera *Thecia*, *Columnopora*, *Boreaster*, *Somphopora*, *Angopora*, *Laceropora*, *Romingerella*, *Fossipora*, and *Araeopora*.

Hill and Stumm (1956), in the family Favositidae, unite in the sub-family Theciinae only the genera *Thecia* and *Romingerella*, *Angopora* being for them synonymous with *Thecia*.

There are important differences. It is convenient to set apart from *Thecia* the forms which possess a wall of the kind which Swann described in *Favosites*, i.e., a median lamella, two thin dark planes on each side, and two borders of perpendicular fibres. Such a microstructure disagrees with the trabecular constitution of *Thecia* chiefly by its continuity along the periphery of corallites. This leads to a withdrawal of the family containing the genus *Thecia* from the taxonomic division which includes the genus *Favosites*. It is therefore impossible to agree with Hill and Stumm, who put *Thecia* in the family Favositidae.

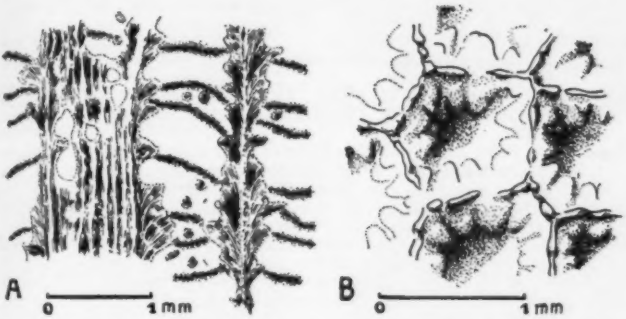
It is not intended in this paper to examine in detail all the genera mentioned above. The authors' descriptions are sufficient to remove *Columnopora*, of which Nicholson's figures exhibit a black median plane in the walls ; *Boreaster* and *Fossipora* which have regularly rounded pores; *Donetzites*, put by Sokolov in the family *Cleistoporidae*, etc. The only genera which remain to be considered, as regards their close relationship to *Thecia*, are *Romingerella and Angopora*, the latter being regarded by some writers as identical with *Thecia*.

I have been able to study at the British Museum (Nat. Hist.) the slides of Jones, author of the genus *Angopora*. The collections of the Faculté des Sciences, Paris, contain fine colonies from Visby (Gotland), belonging to the species *A. hisingeri* Jones. This material afforded numerous thin sections.

To the description by Jones need only be added data about the microstructure: the skeleton is of a trabecular nature. In longitudinal slides the banded appearance is readily perceptible, the centre of the trabeculae being generally whitish (Text-fig. 2). In transverse sections the trabeculae are seen to be of small size, without the radial lengthening encountered in *Thecia swinderniana*. But other macroscopic characters separate *Angopora* from *Thecia*: pores are present in *Angopora*, although they are scarce in depth; the superficial aspect of colonies of *Angopora* is very unlike that of *Thecia*; *Angopora* has a skeleton much less massive than *Thecia*. It is sufficient to compare Text-fig. 2, showing a corallite in a fairly thickened area, with the photograph of *T. swinderniana* from Dudley to be certain of that. It is, therefore, considered that the genus *Angopora* is perfectly valid. From its trabecular nature it is a neighbour of *Thecia*. In a recent paper, D. Le

Maitre has similarly concluded that *Angopora* is not synonymous with *Thecia*.

Specimens of *Romingerella* have not been examined. However, the characters shown by Amsden's photographs seem to be like those of *Angopora*. Unfortunately, the pictures of slides accompanying Amsden's work are not very clear, the sections being too thick, or the material poorly preserved. Nevertheless, the clear patches, more or less aligned in the middle of the walls (as exhibited in his pl. 22, figs. 4 and 5), are quite like what is seen in the slides of *Angopora*. We



TEXT-FIG. 2.—*Angopora hisingeri* Jones. A, longitudinal section showing the banded appearance of a wall, and the whitish median axis of a trabecula; B, superficial aspect of a corallite in a fairly well thickened area.

consider that *Romingerella*, by reason of priority, must be rejected, and the species *Thecia major* Rominger, 1876, becomes *Angopora major* (Rom.).

CONCLUSIONS

It appears that only the genera *Thecia* Edwards and Haime and *Angopora* Jones should be retained in the family Theciidae. This family does not exactly agree with that of Edwards and Haime of 1850, in which those authors included forms referable to *Favistella* and *Columnaria*.

The content of the sub-family Theciinae in the classification of Hill and Stumm agrees perfectly with our concept of the family Theciidae. One of the main characters here emphasized for the genera *Thecia* and *Angopora* is the trabecular nature of the skeleton. It is very evident that further careful revision of the great number of forms among the Tabulata which remain insufficiently known may eventually increase the content of the family Theciidae. As regards the position of the family Theciidae in the Tabulata, it would be premature to suggest taxonomic unities of superior order than families.

ACKNOWLEDGMENTS

I wish to thank Dr. H. Dighton Thomas for allowing me to examine specimens in the collection of the British Museum (Nat. Hist.), for advice about fieldwork, and for correction of the typescript. My visit to England was made possible by a grant of the Centre National de la Recherche Scientifique.

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EXPLANATION OF PLATE X

Thecia swinderniana (Goldfuss)

FIG. 1.—Transverse section showing the vertical trabeculae, limited by accumulation of black matter, × 22, Much Wenlock. (Slide The-5-L_2, Coll. Lafuste).

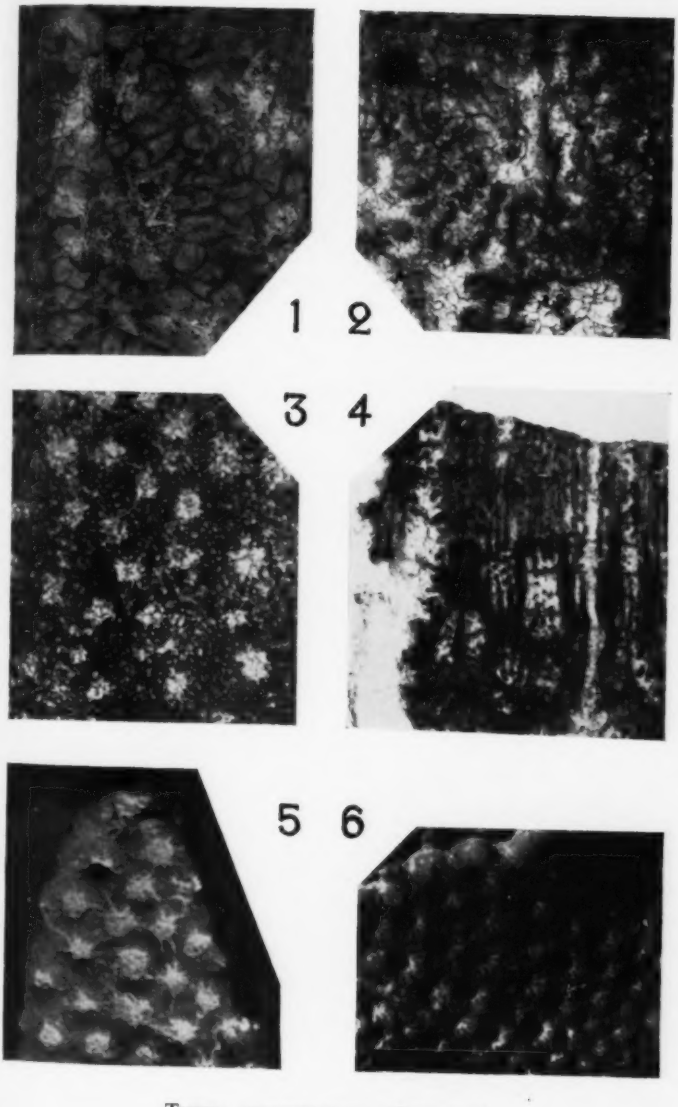
FIG. 2.—Section of a calicle, showing the radiate lamellae, constituted by a dark median plane and normal fibres, × 28, Much Wenlock. (Slide The-1-L_1, Coll. Lafuste).

FIG. 3.—Transverse section exhibiting minute, whitish patches between the corallites, × 10, Dudley. (Slide The-2-T_1, Coll. Lafuste).

FIG. 4.—Longitudinal section, showing the banded appearance of the skeleton, × 13, Much Wenlock. (Slide The-1-L_3, Coll. Lafuste).

FIG. 5.—Specimen from Much Wenlock showing a weathered surface with the false "pores" uniting adjacent calicular pits, × 6·5.

FIG. 6.—Specimen from Dudley showing the thin summit of the radiating lamellae, × 6.



THECIA SWINDERNIANA (GOLDFUSS)

The Upper Jurassic Faunas of Southern Israel

By R. G. S. Hudson

Abstract

Upper Jurassic faunas from Wadi Hathira (Kurnub Anticline), Southern Israel, are listed and allocated to the Callovian, Lower Oxfordian, Argovian, and Sequanian.

Introduction

A GREAT interscarp depression in the desert of the northern Negev of Southern Israel, about 35 km. south-east of Beersheba, was formed by the erosion, by the Wadi Hathira and W. Madsus, of the crest of the S.W.–N.E. asymmetrical Kurnub Anticline. Rocks exposed are the Judea Limestone (Cenomanian–Turonian), which forms the high inwardly-facing outer escarpments breached only in one place by the Pirtsah gorge, the Nubian Sandstone (Albian), which forms the inward slopes, and the Kurnub Limestone (Upper Jurassic), which forms the inner escarpments and the floor of the depression.

Though the lithological succession of the Upper Jurassic has been described in some detail, little has been said of the faunal succession and no detailed age allocation has been made. Fossils are abundant and varied, and the succession could quite well be used as a standard one for comparison with other Jurassic successions in the Middle East. Large collections of fossils have been made by the geologists of the Iraq Petroleum Company and these are now being named and described. Sufficient has been done to make it now possible to allocate the various parts of the succession to the Upper Jurassic Tethyan stages and to make preliminary comparisons with the other successions of the Middle East and North and East Africa.

Most of the fossils were collected by L. Damesin and S. Nasr, some by A. H. Smout and some by the author. Many thus collected are now housed in the Geological Departments of the University of Oxford, the Hebrew University, Jerusalem, and the British Museum (Natural History). In this paper numbers preceded by H, P, R are the registration numbers of the specimens in the collections of the Department of Geology, British Museum (Natural History), London.

The author here records his thanks to those geologists of the Iraq Petroleum Company whose work made this paper possible, and in particular to L. Damesin who, with S. Nasr, mapped the area and compiled the vertical sections, and who so generously made their knowledge available to the author. Permission to publish this paper has been generously given by the Directors and Chief Geologist of the Iraq Petroleum Company. F. Gosling helped with the identification of the *Trocharea*, L. F. Spath determined the ammonites, and L. R.

Cox named most of the gasteropods and lamellibrachs. To all the above the author records his sincere thanks.

Previous Work

A generalized lithological succession, showing 227 m. of marls and marly limestones, was first established in 1930–33 for the Iraq Petroleum Company by F. E. Wellings and L. Damesin, some of the fossils collected being identified by J. A. Douglas. This succession and the identified fauna was published by Blake (1936), and Blake and Goldschmidt (1947). The succession was considered to range from Callovian to Sequanian, though there was no allocation of the various parts of the succession to particular stages.

In 1945–46 a more detailed survey was made by L. Damesin and S. Nasr, and a detailed vertical section, showing a total thickness of 212 m. of marls and marly limestones, was compiled. Large collections of fossils were made and keyed to the vertical section. It is this detailed section and the fossils then collected which is the basis of this paper. A summary of this succession was published by Shaw (1947), but no diagnostic fossils were given and the age of the beds given as Jurassic only.

Earlier, in 1941, fossil collections had been made by A. H. Smout but not closely keyed to the succession. The microfauna of various samples then collected was determined by F. R. S. Henson and later published (Henson, 1948a, b). In 1946 fossils, mainly stromatoporoids and corals, were collected by the author and descriptions of some published (Hudson, 1956, 1958). A columnar section by Y. Bentor of the Jurassic of Wadi Hathira showing generalized lithology was published by Ball and Ball (1953). The beds shown totalled 157·8 m. ; no fauna was given and the age indicated as Jurassic only. A general account of the geology of the Hathira area was given by Wiener (1955), and the course and significance of the Kurnub Anticline have been discussed in various papers by Picard (as 1951) and Bentor and Vroman (1954).

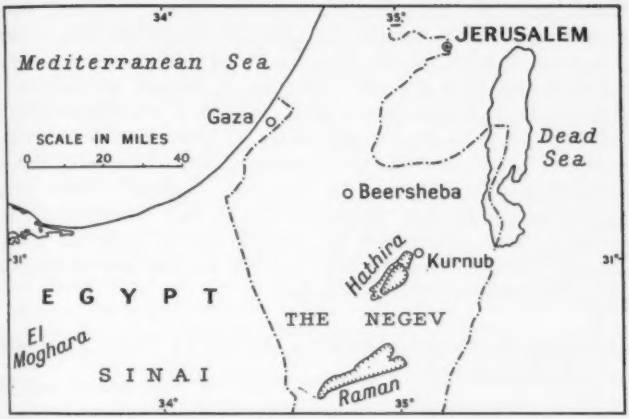
A 50 m. boring put down in 1951 near the crest of the anticline passed through marine limestones and shales (Wiener, 1955).

Faunal Stratigraphy

The Kurnub Limestone consists of limestone, marly limestone and marl, generally buff coloured, though sometimes the marls are reddish and the limestones, especially in the upper part, chalky and light coloured. Distinctive beds are rare, one of the more important being an oolitic limestone, 1 mm. thick, in the upper part of the succession. In general, the proportion of marl and limestone is the main difference between one bed and the other, or between one set of beds, and the other, a distinction not easy to express in the field. Lateral variation

in both lithology and thickness is also present. As a result it is not usefully possible to recognize lithological units, much less to divide the succession into formations.

The fauna is of Tethyan phase, comparable to that of the shelf and reef limestones of the Jurassic both north and south of the Mediterranean. Ammonites are rare and those found are of Tethyan phase: Tethyan and not Western European stage-names are therefore used.



TEXT-FIG. 1.—Locality map Southern Israel and Sinai.

These stage-names have the significance of their authors, Marcou, 1848, and Gressly, 1867 (see Arkell, 1956, p. 93), a significance now adopted by most workers on the Tethyan Jurassic. It is important to note that the Oxfordian is used here, as in Tethyan stratigraphy, as the equivalent of the lower part (*mariae-cordatum* zones) of the Oxfordian of Western Europe. The Rauracian is here considered as the coral-stromatoporoid facies (*Shuqraia* Limestones and Marls of Kurnub) of the uppermost Argovian.

The Jurassic beds of Kurnub are divided as follows :—

5. *Cladocoropsis* Marls and Limestones.
   24 m., Sequanian.
4. *Shuqraia Limestones* with Marl.
   58 m., Argovian.
3. *Somalirhynchia — Putealiceras* Marls and Limestones.
   30·5 m., Lower Oxfordian.
2. *Eligmus — Grossouvria* Marls with Limestone.
   49 m., Upper Callovian.

1. *Eligmus — Erymnoceras* Limestones and Marls.
50 m., Lower and Middle Callovian.

As might be expected, the various faunas of Kurnub are most like those of Moghara, Sinai, to the south-west (Douvillé 1916 ; Moon and Sadek, 1921 ; Hoppe, 1922 ; Cossmann, 1926 ; Tromp, 1951), and of the Lebanon and Anti-Lebanon to the north (Krumbeck, 1905 ; Dubertret, 1954, 1955 ; Haas, 1955). They are, however, not identical. Whereas the Callovian—Lower Oxfordian beds of Kurnub agree in fauna, general lithology, and thicknesses with those of Moghara, there is no close similarity between the Argovian—Sequanian strata of the two areas. But, though the Callovian–Lower Oxfordian strata of the Lebanon have little similarity with those of Kurnub, the Argovian–Sequanian of both areas have much in common. Comparable relationships also apply to more distant areas : Callovian–Lower Oxfordian faunas of Kurnub, and Ethiopia, Somaliland, and southern Arabia are very much alike, whereas the Argovian–Sequanian faunas have similarities with those of the Mediterranean. Such differences can be summed up by stating that in Callovian–Lower Oxfordian times, Kurnub belonged to the Ethiopian Province, but that later its affinities were with the Mediterranean Province.

1. Eligmus–Erymnoceras *Limestones and Marls ; 50 m., Lower and Middle Callovian.*

The lower part (21·2 m.) of these beds are buff-coloured silty marls with occasional marly limestones. Layers of gypsum occur in the lower marls, haematitic bands which weather reddish are not uncommon, while 8 m. from the base of these beds there is a reddish brown sandstone about a metre thick. In the upper part (28·8 m.) of these beds limestones are more common, tend to be lighter in colour and are generally more fossiliferous especially one, 4 m. thick, at their base and another, 7·50 m. thick, at their top. Lamellibranchs and gasteropods, mostly internal casts, and echinoid and crinoid debris are the common fossils. *Eligmus* spp. occur throughout. Corals, mainly *Calamophyllia*, are not uncommon. In several beds of marl *Trocharea* (*Trochoplegma*) cf. *tenuilamellosa* (Gregory) occurs abundantly (R 41235–53). The type of this form was from the Bathonian–Callovian of Cutch ; its abundance recalls the *Anabacia* beds of Moghara, Sinai. Foraminifera include *Trocholina palastiniensis* Henson, *Nautiloculina oolithica* Möhler, and in the upper part of the group, *Valvulinella jurassica* Henson. The holotype (P 38487) and the paratypes (P 38474–77) of *T. palastiniensis* Henson (1948a) were all collected from these beds from the sandstone upwards. The upper beds contain *Erymnoceras* aff. *dorothea* Spath, *Thysanolytoceras* cf. *adeloides* (Kudernatsch), *Pachyceras* spp., and

Nautilus (*Paracenoceras*) cf. *giganteus* d'Orb. The fauna, according to L. F. Spath, compares well with the *Erymnoceras* fauna of Moghara, Sinai, and is of Middle Callovian age. Such an *Erymnoceras* fauna also occurs in the Anti-Lebanon near Mt. Hermon (Dubertret, 1955 ; Arkell, 1956) and in Central Arabia in the lower part of the Tuwaiq Mountain Limestone (Arkell, 1952). Brachiopods, mostly terebratulids, occur throughout, though most of those in the lower part are crushed and not identifiable. The following occur in the uppermost 7·50 m. of marly limestone with *Erymnoceras : Daghanirhynchia* sp., *Somalirhynchia bihensis* Muir-Wood, *S. somalica* (Dacqué), *Bihenithyris weiri* Muir-Wood, *Somalithyris bihendulensis* Muir-Wood, *Striithyris somaliensis* Muir-Wood (also occurring in the lower part of these beds), *Terebratula* cf. *bisuffarcinata* Noetling, *T.* cf. *subsella* Leymerie, and *Zeilleria* sp., all recorded by Muir-Wood from the Bihen Limestone of Somaliland (Macfadyen *et al.*, 1935).

Identified lamellibranchs and gastropods are as follows (the number following the name is the number identified) : *Myoconcha*, 3 ; *Mytilus*, 1 ; *Modiolus imbricatus* (J. Sowerby), 2 ; ?*Musculus somaliensis* Cox, 1 ; *Brachidontes* (*Arcomytilus*) *laitmairensis* (de Lor.), 3 ; *Eligmus polytypus* Deslongchamps, 8 ; *Eligmus weiri* Cox, 3 ; *Liostrea dubiensis* (Contejean), 1 ; *Liostrea* (*Catinula*) *sandalina* (Goldfuss), 1 ; *Lopha* cf. *solitaria* (J. de C. Sowerby), 4 ; *Gryphaea* cf. *dilatata* (J. Sowerby), 2 ; *Chlamys* (*Aequipecten*) cf. *palinurus* (d'Orb.), 1 ; *Chlamys* (*Aequipecten*) *syriaca* Cossmann, 3 ; *Entolium*, 1 ; *Lima* (*Plagiostoma*) cf. *callovica* Cossmann, 3 ; *Anisocardia minima* (J. Sowerby), 1 ; *Astarte*, 1 ; *Isocyprina boonei* Cossmann, 1 ; *Lucina* cf. *cardioides* d'Archiac, 3 ; *Mactromya aequalis* Agassiz, 1 ; *Protocardia*, 1 ; *Pterocardia* cf. *corallina* (Leymerie), 1 ; *Ceratomya* cf. *concentrica* (J. de C. Sowerby), 1 ; *C. excentrica* (Roemer), 4 ; *C.* cf. *plicata* Agassiz, 1 ; *Ceromyopsis arabica* Cox, 3 ; *Pholadomya* cf. *deltoidea* (J. Sowerby), 1 ; *P. lirata* (J. Sowerby), 6 ; *Homomya inornata* (J. de C. Sowerby), 1 ; *Arcomya latissima* Agassiz, 2.

Nummocalcar, 2 ; *Proconulus* cf. *piettei* (Hébert and Deslongchamps), 1 ; *Ataphrus* cf. *ovulatus* (Hébert and Deslongchamps), 1 ; *Pseudomelania deslongchampsi* Cossmann, 2 ; *P. scarburgensis* (Morris and Lycett ?) Cossmann, 4 ; *Rigauxia ferenuda* Cossmann, 6 ; *Procerithium* (*Cosmocerithium* ?), 1 ; *Ampullospira* cf. *stricklandi* (Morris and Lycett), 7 ; *A.* cf. *ranvillensis* (d'Orb.), 1 ; *Globularia* cf. *amata* (d'Orb.), 1 ; *G. formosa* (Morris and Lycett), 2 ; *G. michelini* (d'Orb.), 5 ; *G.* cf. *pertusa* (Laube), 1 ; *G.* cf. *zetes* (d'Orb.), 1 ; *Globularia*, 6 ; *Naricopsina montreuilensis* (Hebert and Deslongchamps), 1 ; *Diarthema* ?, 1 ; *Aporrhais*, 1 ; *Harpagodes* cf. *wrighti* (Morris and Lycett), 6 ; *Cossmannea*, 1 ; *Nerinella*, 1 ; *Bactroptyxis*, numerous ; *Cylindrites* cf. *cylindricus* Morris and Lycett, 6.

2. Eligmus-Grossouvria *Marls with Limestones;* 49 *m., Upper Callovian.*

These beds are buff and grey, gypsiferous, calcareous marls, mainly unfossiliferous, with occasional beds of fossiliferous marly limestones about 2 m. thick. At the top of the group a white, massive, chalky limestone, 4·50 m. thick, and with abundant fossils including corals, echinoids and brachiopods, is a distinctive marker bed.

Eligmus and *Lopha solitaria* occur throughout. *Grossouvria* sp. (group of *G. variabilis* Lahusen sp.) is common, with other ammonites, in a very fossiliferous rubbly marly limestone, 3·50 m. thick and 9·5 m. from the top of the group. *Obtusicostites*, *Kinkeliniceras*, and ? *Euaspidoceras* occur in the uppermost limestone. Both ammonite faunas were considered by Spath to be of Upper Callovian (Divesian) age.

The foraminifera include *Valvulinella jurassica* (Henson), *Trocholina palestiniensis* Henson and *Nautiloculina oolithica* (Möhler). *Trochararea* sp. (R 41254–68, R 41284) are still common especially in the marly limestone with *Grossouvria*. *Amphiastraea gibberosa* (Gregory) and abundant *Stylina* spp. occur in the uppermost limestone. Common crinoid and echinoid debris include *Millericrinus* and *Apiocrinus* ossicles and calices and *Cidaris* and *Rhabdocidaris* spines. *Pileus* cf. *pileus* Agassiz and *Pygaster umbrella* Agassiz also occur. Brachiopods, mostly terebratulids, are not common, except in the uppermost limestone. They include *Bihenithyris barringtoni* Muir-Wood, *B. weiri* Muir-Wood, *Cererithyris* spp., *Somalithyris bihendulensis* Muir-Wood, *Striithyris somaliensis* Muir-Wood, *Terebratula* cf. *subsella* Leym., *Zeilleria* sp., *Somalirhynchia bihenensis* Muir-Wood, and, in upper part only, *Somalirhynchia africana* Weir. Gastropods and lamellibranchs are as follows: *Myoconcha*, 1; *Modiolus* (*Inoperna*) *plicatus* (J. Sowerby), 1; *Brachidontes* (*Arcomytilus*) *laitmairensis* (de Lor.), 1; *Musculus somaliensis* Cox, 3; *Eligmus aualites* (Stefanini), 3; *E. rollandi* Douvillé, 2; *Lopha solitaria* (J. de C. Sowerby), 9; *L. gregarea* (J. Sowerby), 2; *Lopha*, 1; *Liostrea* (*Catinula*) *sandalina* (Goldfuss), 2; *Gryphaea*, 1; *Exogyra*, 1; *Chlamys* (*Aequipecten*) *syriaca* Cossmann, 1; *C.* (*Radulopecten*) *scarburgensis* (Young and Bird), 2; *Lucina* cf. *cardioides* d'Archaic, 1; *Fimbria* cf. *buvignieri* Deshayes, 1; *Mactromya* cf. *aceste* (d'Orbigny), 2; *Ceromyopsis* cf. *arabica* Cox, 2; *Pholadomya protei* Brongniart, 3; *Pleuromya* cf. *uniformis* (J. Sowerby), 1; *Anisocardia*, 1; *Emarginula*, 1; *Pleurotomaria*, 1; *Ataphrus* cf. *ovulatus* (Hébert and Deslongchamps), 1; *Discohelix*, 4; *Pseudomelania deslongchampsi* Cossmann, 6; *P. scarburgensis* (? Morris and Lycett) Cossmann, 7; *Rigauxia ferenuda* Cossmann, 1; *Procerithium* (*Cosmocerithium*), 2; *Globularia* cf. *chauviniana* (d'Orb.), 3; *G. formosa* (Morris and Lycett), 1; *G.* cf. *zetes* d'Orb., 4; *Aporrhais*

(*Quadrinervus* ?) cf. *elegans* (Piette), 1 ; *Aporrhaidae*, 5 ; *Dicrolema* ?, 2 ; *Harpagodes* cf. *wrighti* (Morris and Lycett), 9 ; *Nerinea*, 1 ; Nerineidea, 3 ; *Nerinella*, abundant *Cylindrites*, 3.

3. Somalirhynchia–Putealiceras *Marls and Limestones ;* 30·5 *m., Lower Oxfordian.*

These beds are mainly interbedded marls and limestones with marls predominant. In general the fauna is one of brachiopods, echinoids and abundant corals. The brachiopods include *Burmirhynchia jirbaensis* juv. Muir-Wood, *Daghanirhynchia* sp., *Somalirhynchia africana* Weir common, *S. africana jordanica* (Noetling), *S. bihendulensis* Muir-Wood, *S. bihenensis* Muir-Wood, *S. somalica* (Dacqué) common, *Kingena* sp., *Striithyris somaliensis* Muir-Wood common, *Terebratula* cf. *curtirostris* Krumbeck, *T.* cf. *subsella* Leymerie abundant, *Zeilleria* sp. The fauna is essentially that of the upper part of the Bihen Limestone of Somaliland (Macfadyen *et al.*, 1935) considered to be of Divesian age. This age is confirmed by the occurrence in a limestone group, 5 m. thick and 6 m. above the base of the group, of *Putealiceras* and *Sublunoceras* considered by Spath to be of Lower Oxfordian (Upper Divesian) age. It is probable that this fauna is the equivalent of the well-known Lower Oxfordian *Creniceras rengerri* fauna of the Lebanon (Dubertret, 1955 ; Haas, 1955).

The gastropod-lamellibranch fauna differs little from the beds below. It is as follows : *Myoconcha*, 1 ; *Brachidontes* (*Arcomytilus*) *laitmairensis* (de Lor.), 1 ; *Modiolus* (*Inoperna*) *plicatus* (J. Sowerby), 1 ; *Musculus somaliensis* Cox, 4 ; *Liostrea dubiensis* (Contejean), 1 ; *Liostrea* (*Catinula*) cf. *sandalina* (Goldfuss), 1 ; *L. gregarea* (J. Sowerby) (= *Alectryonia rastellaris auctt.* ; = *Arctostrea avita* Douvillé 1916), 1 ; *Exogyra nana* (J. Sowerby), 5 ; *Protocardia*, 2 ; *Ceromyopsis* cf. *arabica* Cox, 1 ; *Pholadomya protei* (Brongniart), 1 ; *Anisocardia tenera* (J. Sowerby), 1 ; *Pleurotomaria*, 1 ; *Discohelix* cf. *douvillei* Cossmann, 1 ; *Pseudomelania* cf. *deslongchampsi* Cossmann, 3 ; *Globularia* cf. *zangis* (d'Orb.), 1 ; *Globularia*, 6 ; *Aporrhais*, 1 ; *Harpogodes* cf. *wrighti* (Morris and Lycett), 2 ; Procerithiidae, 1 ; *Nerinea*, 1 ; *Cylindrites plicifer* Cossmann, 1 ; *Cylindrites*, 2.

Corals are abundant throughout ; they include *Actinaraea*, *Calamophyllia*, *Comoseris*, *Enallhelia*, *Microsolena*, *Montlivaltia* common, *Stylina* and *Thamnasteria* : *Trocharea* sp. (*Chomatoseris* cf. *acaulis* Gregory sp., R 41269–82, 85, 88) is not found above the limestone 6 m. from the base of the group. Foraminifera include *Valvulinella jurassica* and *Nautiloculina oolithica*. *Millericrinas* ossicles and cidarid spines occur in great abundance.

4. Shuqraia *Limestones with Marls ; 58 m., Argovian.*

These very fossiliferous beds consist of a lower limestone group, 12·5 m. thick, the lowest limestones light-grey, partly silicified and weathering dark-buff, the remainder usually fine-grained (chalky), weathering white but occasionally marly and then weathering buff ; a middle group, 24 m. thick, of buff-coloured marly limestones and marls with, 12 m. from its base, 6 m. of well bedded and very fossiliferous white limestone ; and an upper group of gypsiferous marls and marly limestones, white or buff, with a marked, soft, brown oolitic limestone, 1 m. thick, at its base. The lower group contains a normal molluscan fauna, with echinoids, " stromatoporoids ", corals, especially *Montlivaltia*, and, quite abundant, Rhynchonellids. Corals and " stromatoporoids " are abundant in the middle group, often to the exclusion of other fauna, except in the 6 m. white limestone which contains abundant *Globularia* and *Purpuroidea*. The upper group, contains gastropods, lamellibranchs, abundant echinoids and numerous " stromatoporoids ".

The corals, which have not been examined in detail, include most of the genera common in the Tethyan Upper Jurassic (Rauracian) and many of the species described by Felix from the *Cidaris glandaria* Limestones of the Lebanon : *Trocharea* does not occur. The common " stromatoporoid " is *Shuqraia* which occurs throughout ; *Promillepora kurnubi* Hudson, *P. pervinquieri* Dehorne, *P. douvillei* (Dehorne) ; *Steinerina somaliensis* (Zuff.–Com.), *Actostroma damesini* Hudson, *A. nasri* Hudson and *A. kühni* Hudson have been described from the upper beds (Hudson, 1956, 1958). *Stromatoporina* also occurs in these beds. Echinoids, not yet named, are mostly cidarids ; crinoids which are abundant are mostly *Isocrinus*. The brachiopods, though not common, include *Burmirhynchia* cf. *jirbaensis* Muir-Wood, *Somalirhynchia africana* Weir, *S. jordanica* (Noetling), and *Terebratula* cf. *subsella* Leym. from the lower beds, *Somalirhynchia africana* and *S. mesoloba* Muir-Wood from the middle beds, and *Terebratula curtirostris* Krumbeck from the upper beds. The *Somalirhynchia* fauna is comparable with that described by Muir-Wood (Macfadyen *et al.*, 1935) from the upper part of the Bihen Limestone and the lower part of the Gadoaleh Shale (Argovian) of Somaliland while *T. curtirostris* was described from the *C. glandaria* beds of the Lebanon. Named gastropods and lamellibranchs are as follows (the number following the name is the number of named specimens of that form) : *Palaeonucula menkii* (Roemer), 1 ; *Myoconcha*, 1 ; *Mytilus jurensis* Roemer (= *M. alatus* Krumbeck), 11 ; *Liostrea dubiensis* (Contejean), 6 ; *L.* (*Catinula*) *sandalina* (Goldfuss), 14 ; *Lopha eruca* (Defrance), (= *Alectryonia hastellares* auctt. ; = *Arctostrea amor* Douvillé 1916),

1 ; *Exogyra nana* (J. Sowerby), 2 ; *Chlamys* (*Radulopecten*) cf. *inaequicostata* (Phill.), 1 ; *Lucina* spp., 11 ; *Fimbria buvignieri* (Deshayes), 12 ; *Fimbria* cf. *subclathrata* (Contejean), 6 ; *Mactromya* cf. *aceste* (d'Orb.), 1 ; *Ceratomya excentrica* (Roemer), 1 ; *Protocardia*, 1 ; *Ceromyopsis striata* (d'Orb.), 1 ; *Pholadomya protei* (Brongniart), 2. *Chartroniella*, 2 ; *Rothpletzella*, 3 ; *Ataphrus* cf. *ovulatus* (Hébert and Deslongchamps), 1 ; *Brasilia erina* (d'Orb.), 1 ; *Lissochilus* cf. *concinnus* (Roemer), 1 ; *Pseudomelania*, 1 ; *Diatinostoma* (*Ditretus mairei* Cossmann, 1 ; *Globularia amata* (d'Orb.), 1 ; *Globularia* cf. *georgeana* (d'Orb.), 8 ; *G.* cf. *millepora* (Buvignier), 1 ; *G.* cf. *phasianelloides* (d'Orb.), 3 ; *G. rupellensis* (d'Orb.), 4 ; *Globularia*, 8 ; *Lobotoma* ?, 1 ; *Cuphosolenus matronensis* (de Loriol), 1 ; *Aporrhais*, 2 ; *Harpogodes*, 1 ; *Procerithium* (*Xystrella*), 1 ; *Purpuroidea*, 14 ; *P.* cf. *lapierrea* (Buvignier), 1 ; *Nerinea orbignyana* Zeuschner, abundant ; *N.* cf. *salomoniana* Cotteau ?, Delpey, 1 ; *Nerinea*, 4 ; *Cossmannea* cf. *tuberculosa* (Defrance), 1 ; *Cossmannea*, 9 ; *Nerinella altenensis* (d'Orb.), 1 ; *N. ornata* (d'Orb.), 1 ; *Nerinella*, 1 ; *Acteonina*, 1.

The holotype (P 39081) of the foraminifer *Valvulinella wellingsi* Henson (1948b) and that (P 39089) of *Kurnubia palastiniensis* Henson (1948b) were collected from the middle group of these beds, and the holotype (P 39085) of *Valvulinella jurassica* Henson (1948b) from the upper group. In addition to these forms the following have also been recorded : *Nautiloculina oolithica* Möhler, *Pfenderina neocomensis* (Pfender), *Pseudocyclammina sequana* Möhler and *Pseudocyclammina* sp.

5. Cladocoropsis *Marls and Limestones ; 24 m., Sequanian.*

These beds consist of a lower group of marls and limestone, 14·5 mm. thick ; a middle limestone, grey, finely crystalline, often cherty, generally massive, and 5·5 m. thick ; and an upper 4 m. of marl and brown limestone. *Cladocoropsis* cf. *dubertreti* Hudson (= *Lovcenipora* auctt.) occurs throughout : in the middle limestone it is silicified and the only fossil. *Cladocoropsis* Limestones are well known from the Middle East and particularly from the Lebanon (Heybroek, 1942 ; Hudson, 1953, 1954) where they form the upper part of the *Cidaris glandaria* Limestones and are of Sequanian (Lower Kimmeridgian) age.

The lower group of these beds contains a normal fauna of which the following have been identified : *Somalirhynchia smelliei* Weir, cf. *S. africana* Weir, cf. *S. tumida* Muir-Wood, *Mytilus jurensis* Roemer, *Trigonia libanensis* Krumbeck, *Globularia* cf. *rupellensis* (d'Orb.), *G.* cf. *semitalis* (de Lor.) abundant, and *Purpuroidea* sp.

The uppermost 4 m. of this group contains, in addition to a molluscan-echinoid-coral fauna, abundant brachiopods which include

Kingena cubica (Quenst.), *K. orbis* (Quenst.), *K. gutta* (Quenst.), *Zeilleria latifrons* (Krumbeck) and *Rhynchonella drusorum* Krumbeck. These were recorded by Krumbeck from the uppermost Jurassic of the Lebanon in limestones (Couches jaunes ; Bikfaya Lmst., etc.) immediately above the *C. glandaria* Limestones, but like them considered to be of Sequanian age.

6. *Kurnub Sandstone ; Cretaceous.*

The Jurassic is followed by the Kurnub Sandstone, a series of multicoloured marls and sandstones, about 400 m. thick, with, at its base, a haematitic black-weathering breccia containing fragments of Jurassic Limestone. About 155 m. from the base of the sandstone, a marly limestone, about 0·30 m. thick, contains *Knemiceras syriacum* (von Buch), *K.* aff. *attenuatum* Hyatt and *K.* sp. (Basse, 1940) of Albian age.

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CORRESPONDENCE

THE EVIDENCE FOR COSMIC UPWARD PULL IN MOUNTAIN AND LAND UPLIFT

SIR,—It is admitted that lunar or tidal pull or gravitation has an effect on the solid surface of the earth, but it is always stated that the surface returns to its original level. I have examined evidence in various regions and conclude that such a pull has been effective and accumulative and is responsible for much of the uprise and maintenance of land surfaces we see to-day. Briefly stated the reasoning is as follows:—

1. Gravitational pull of the moon and other celestial bodies acts continually on the higher or more massive parts of the earth's surface, tending to pull them upwards, the higher parts more strongly than those below.
2. Cohesion or mass gravitation causes the mountain mass to be attracted together as it comes up.
3. Pressure of water in adjacent oceans tends to reinforce the upward movement and to depress the sea bed in a reverse manner.
4. Metamorphism and crystalline changes in certain rocks below causes heating and softening and makes the pull up more effective. At the same time, it produces a great contraction in volume and this can lead to folding and disturbance in the rocks concerned.

The regions I have examined mainly are England, the Alps, Jamaica, Barbados, Trinidad, and New Zealand. This theory is based on observable evidence and is not mere " wishful thinking ". In this " Geophysical Year " it may be of interest to present such evidence.

EVIDENCE FROM RAISED BEACHES

Raised beaches are generally seen on rocky platforms and not on flat lying adjacent land at lower levels. The one I know best is north of Easington on the Durham coast; a patch of shelly gravel resting on brecciated Magnesian Limestone at the foot of the Shell Limestone Knoll of Beacon Hill. The beach would seem to mark a mild interval after the initiation of the Cheviot Northern or last glaciation. It is overlain by calcreted glacial gravel and by thin glacial drift. On the shore for about a mile round the base of the Knoll, the cliffs are in places strongly slickensided up and down. Among the breccia there have been several fissures filled with late Tertiary or early Glacial red marl and pieces of upper Magnesian Limestone. Some of these have been caught in the movement and are crushed and slickensided, especially on the side facing the Knoll, and they tend to bend over upwards towards the Knoll. The Knoll itself is slickensided vertically on a small scale as I used to see years ago when the railway cutting was being made. The red fissures are seen only in the cliff near the Knoll, and do not occur between tide marks.

If the beach had been due to a temporary rise of sea level it should have left traces on the lower ground, but it has not. It was deposited at sea level, then a rise of the brecciated rock occurred. There are in the beach no pebbles of the fossiliferous rock from the Knoll which rises immediately to the west. The inference would seem to be that the Knoll was then not so prominent as it is now. During post-glacial time the Knoll may have risen and dragged up the platform of brecciated rock on its seaward flank, the red fissures acting as a sort of lubricant in the process.

A curious piece of negative evidence is that, with the exception of a mass from the higher part of the reef in the railway cutting between Castle Eden and Hesleden, I have never found a piece of Shell Limestone in the drift, never a fossil such as *Productus horridus*. One would have supposed that if the knolls such as Humbledon and Tunstall Hills were as prominent as they are now, they would have provided many pebbles to the glacial drift. I think that after the removal of the ice sheet the landscape was improved upon or exaggerated, and I can see no way this could have come about, except by a differential pull up on the more elevated masses, leaving the lower parts to stay where they

are or to go down under pressure of sea water. The Beacon Hill raised beach at 80 feet is almost in view of the submerged forests of Hartlepool and Roker, which continue under the North Sea.

The Permian of East Durham has in the Tertiary period been covered by Trias, Lias, Jurassic, and Chalk, a series possibly 5,000 feet thick. As this was denuded away most of North and Central England remained a land surface, the uprise keeping place with the denudation. It has never been 5,000 feet high and then denuded down. During the same period in the Isle of Wight and on the South Coast, the Chalk and Eocene have been turned up on end, but with much less denudation and much less rise. To my mind some explanation other than the crude one of a cooling and contracting earth must be sought to explain these facts.

The Alps

The structure of the Alps is reasonably clear if the writers since 1900 will only allow it to be so. Starting on the Molasse near Lucerne the Rigi conglomerate is raised against the Alpine rocks, then the Klippen Masses of the Mythen, Pilatus, and others rest on Flysch. The Cretaceous and Jurassic follow, often back-folded as one sees along the Axenstrasse. The high calcareous Alps and the St. Gothard massif have infolded masses of Secondary strata, generally represented as down loops. Those I have seen look more like slices of strata with the higher beds facing towards the greater Alpine uplift. Almost flat-lying gneiss and schist of Tessin is followed southwards by infolded Carboniferous at Manno, and then near Lugano the Permian and Trias are turned over towards the south, and finally the Tertiary on the southern edge.

I wrote a paper dealing with the so-called exotic granite blocks in the Habkerenthal near Interlaken. After examination I concluded that the specimen often figured had been a pocket of pebbles of granite, pegmatite, limestone, and nummulitic green-sand that had been welded together and turned up on end in the Wild Flysch.[1] The rounded base and the three partly detached upper pieces suggested some drawing-up process.

Before I accept the Klippen as relics of vast overthrust sheets of the last period of Alpine movement I should like some borings, such as are put down in oil-bearing countries, to show on what they rest and whether the Molasse passes under them as present-day sections generally show. They may have belonged to some earlier period of slumping in or on the Flysch and have been raised in the general uplift in Miocene times.

The fossils reported from the Mythen and those I sometimes collect on Mt. Pilatus need not have travelled far; they look like local types. The idea of far-transported Nappes is not supported by fossil evidence, whatever the argument may be from facies peculiarities.

The Alps are a range that has a metamorphic core. On the north side the Jurassic and Cretaceous rocks are not schistose, and on the south side near Lugano, at Monte Salvatore, the Trias Esino limestone, and at Monte Generoso the Lias is unaltered. In the central Alps the Jurassic has been involved and metamorphosed. Schists at Griespass and Nufenen with Belemnites, crinoid stems, Liassic Cardinias, etc., are seen and I notice that in the metamorphic knotted schist the Belemnites are not broken or stretched; it is in the less altered shale that they are torn apart and the spaces filled with calcite.

The Furka Pass involvement is one I have seen. The higher or Lias Beds are on the north side facing the high Alps. The Rauchwacke and Verrucano on the south merge into schist and gneiss on which they were deposited. Some of the strata are metamorphosed and closely resemble rock from the northern range of Trinidad. It looks to me like a one-time escarpment that has become turned up on end between gneiss and granite; both have come

[1] This was confirmed in 1952 by Walter Gigon. Verhandlungen de Naturforschenden Gesellschaft in Basel, p. 105, Fig. 17.

up, but that on the north side has risen much more than that on the south side.

At the Joch Pass on the north side of the Alps a similar arrangement, but in reversed order, seems to exist; the Nummulitic Beds are on the south facing the high uplift, the Permian Beds being towards the north.

At the Jungfraujoch, the rock one sees on coming out from the tunnel has been described as gneiss and as granite. Pieces of it closely resemble samples from the northern range from Trinidad, which are metamorphosed sedimentary series. It merges down in the form of thin streaks into the almost unaltered Jurassic limestone below. It has apparently been over-turned towards the north. In none of these localities can I see any reason to suppose that they have been overlain by horizontal Nappe Sheets, now supposedly weathered away. In fact, I know of no section in the Alps where undoubted Protogine gneiss has been thrust over secondary strata.

The Alps are commonly supposed to have been shortened across by 60 or 120 miles. In my last conversation with our lamented friend Doctor G. M. Lees, I said I would be satisfied with about 2 miles. The involved secondary beds, now schistose, must have undergone great contraction with removal of calcite, as one observes in Jamaica or in the Delabole Slates of Cornwall. Internal cohesion rather than any rock pressure from outside could draw them together during the process of uplift with resulting contortion of the strata.

As regards the so-called fan-like structure. This refers to the feature that on the north and south sides the strata tend to be dipping in a reverse direction, The higher east end of Jamaica shows a similar disposition, the marginal beds being over-turned and then flattened out again. The Alps came up out of a Miocene Sea as Jamaica is coming up out of the Caribbean.

The West Indies

Geologists in the past have been fond of representing the West Indies as a uniform uplift with a great but imaginary fault passing through the arc and dividing the outer stratified from the inner volcanic islands. It has to pass of course between the volcanic western part and eastern limestone part of Guadeloupe. Suess, vol. 1, p. 544, makes the erroneous statement that the inner arc is wholly of recent volcanic origin. There are older Tertiary sediments on Martinique and Carriacou. He and others also refer to the West Indies as a sunken mountain chain. When I see Cretaceous shale with fossils at 7,000 feet in Jamaica, I tend to take the opposite view and to look on it as a rising mountain range in process of coming up out of the sea.

It is an arc, but so are most mountain uplifts. Far from being uniform, parts of one and the same island, though made of the same rocks, have a different geological story to tell. The high eastern part of Jamaica differs in its state of metamorphism from the lower western part. The south part of Barbados is a later uplift than the higher main part. The northern range of Trinidad is highly metamorphic while the central range is unaffected. Antigua, on the other hand, looks like a piece of continental land; the old igneous part may have risen and the sedimentary beds gone down round the edges of the island. It has no raised coral rock.

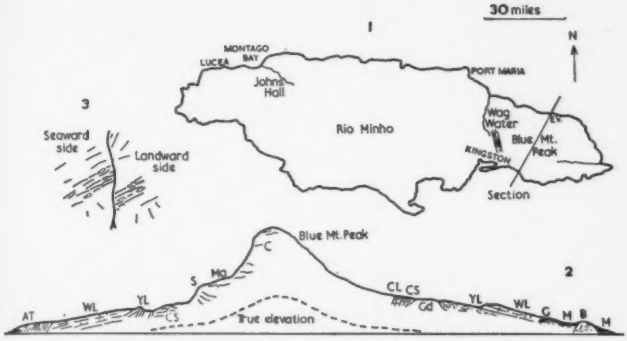
Jamaica

Jamaica is 144 miles from east to west and 49 miles north to south at the widest part and rises to 7,402 feet[1] at Blue Mountain Peak, towards the eastern end, where it is only 25 miles across. All the island was probably covered by white limestone in early Miocene times. It then began to come up in the form of an elongate dome, when the marginal August Town, Bowden, and Manchioneal beds began to be laid down in gradually deepening sea around the edges of the rising land. At the eastern end, measured from

[1] Sawkins in 1865 gives the height of Blue Mountain Peak as 7,385 feet. Like Barbados there is a suggestion that it has risen.

the marginal beds on the north and on the south, Jamaica is a more abrupt uplift than the Alps.

The larger and wider western part rises to not much above 2,000 feet, and a long east to west valley has been eroded down to the Eocene and Cretaceous beds, the Rio Minho Valley. The marginal beds dip off the white limestone at low angles, but at two places on the north coast at Lucea and at Port Maria, the older Eocene shales and conglomerates touch the coast.



TEXT-FIG. 1.—(1) Sketch map of Jamaica to show localities and the position of the Wag Water dislocation and of the section.

(2) Section across Jamaica about 23 miles from the extinct volcano at Low Layton, though Blue Mountain Peak, to 12 miles east of Kingston. It shows the tilting, up-ending, and partial reversal of dip of the marginal beds, north and south of the highest uplifted part of the island.

M. Manchioneal beds, Pliocene. B. Vesicular pillow lavas. G. Globigerina marls, Miocene. W.L. White limestone. Y.L. Yellow limestone, Middle Eocene. C.S. Carbonaceous shale or flysch, Lower Eocene. Gd. Granodiorite. C.L. Cretaceous limestone and shale at Fruitful Vale. C. Cretaceous mudstone at the Peak. Ma. Marble at Abbey Green. S. Serpentine and Westphalia schists. A.T. August Town beds, Upper Miocene, at the south coast.

(3) A section about 6 feet high near the north coast of Jamaica, east of Swift River. The beds are flinty white limestone with *Lepidocyclina*. They dip seawards but a small fault has displaced a band of flint on the north side upwards. This suggests that there has been upward pressure from the direction of the submarine slope.

The higher eastern end of Jamaica is formed of similar beds, but they show a different state of metamorphic alteration. It is separated from the lower lying western area by a band of dislocation called the Wag Water Fault which passes from east of Kingston in a north-westerly direction. This is a complicated band of dislocation which brings up and involves slices of granodiorite. It can be traced for about three-quarters of the distance to the north coast in a north-westerly direction.

Below the western area, the rocks are in places altered by metasomatism. At Johns Hall, in the Montego Bay region, a fossiliferous Eocene conglomerate with limestone pebbles seems to change, with elimination of the calcite and by growth of ferromagnesian crystals, into an andesitic tuff or agglomerate, and this into a basic andesitic lava which becomes intrusive. At Harkers

Hall, granodiorite is exposed and adjacent to it is a hornfelsed conglomerate in which the pebbles have been drawn out as streaks and over-folded forming a rock which Sawkins called petrosilex. This granodiorite comes up to the base of the white limestone which it seems to marmorize, patches of white crystalline limestone are found in the granodiorite. Below the higher eastern end of Jamaica, the metamorphism is more varied and of a different character. Conglomerates of the Cretaceous and Eocene carbonaceous shale series can be seen passing into Serpentine at Moy Hall and Arntully ; into Chinese steatite up the Rio Grande; into schist at Abbey Green. These changes can be traced in the field and specimens collected. The actual Blue Mountain Peak is formed of scarcely altered shale and conglomerate and Cretaceous fossils are found at 7,000 feet. I attribute the higher uplift of Eastern Jamaica to a different condition of metamorphism, a plastic softening which allows a pull up but a less liability to fall back again. This material has undergone great internal contraction with removal of limestone and is often much slickensided.

Jamaica, like the Alps, exhibits what is called " Fan Structure ". The solid compact mass of white limestone is rarely disturbed or tilted, but the Blue Mountain Cretaceous formation has risen more than 3,000 feet since the white limestone was denuded off it.

The marginal beds round the flanks of the eastern part are often raised on end so as to dip vertically or become slightly reversed. Later beds further away from the raised mass have remained flat. This condition of the rocks is seen on both north and south sides of the Blue Mountain uplift.

Text-fig. 1 is intended to represent a cross-section from the so-called extinct volcano on the north coast to the Cane River, east of Kingston, on the south coast. The volcano is a ridge of basaltic lava which has flown out into globigerina marls, probably early Miocene. It is no part of a crater, but is a dead mass that was below sea level and was overlain by Manchioneal beds of Pliocene age. It has come up possibly because the rock is magnetic or because it is a solid mass, and has tilted the covering beds on both its seaward and landward sides. Going south down a depression and up the slope away from the basalt, we find late Tertiary globigerina marls dipping to the north, while a little further up these beds stand on end, and where they adjoin the thick white limestone they are slightly reversed. The white limestone with *Lepidocyclina* has been dragged up as a compact mass and has tilted the less solid marginal beds on its flank. The white, with the yellow limestone at its base, ends in an escarpment at about 2,000 feet, when the Blue Mountain complex of early Eocene Flysch and Cretaceous beds appears uncomformably below the covering beds.

South of the Blue Mountain mass the succession is repeated. A north-facing scarp of yellow and white limestone, with lower down, near the sea, August Town and marginal late Tertiary beds. In a quarry near Cane River, they are turned up on end or slightly reversed, but they are flattened out when they are well away from the upraised mass of white limestone.

On the flatter south and south-west parts of Jamaica are three or four minor subsidiary uplifts of white limestone. West of Kingston Harbour is the Port Henderson mass, with its much discussed section at the Lazaretto. It has a core of hornblende schist and amphibolite with hornfelsic material. I concluded this to be metamorphic Eocene carbonaceous shale series overlain by white limestone with *Dictyoconus*. There is a marble layer at the top in which I found remains of the *Dictyoconus* still recognizable. The softened mass below may have enabled it to be pulled up, and in doing so, it has tipped up a series of August Town beds which now dip away from it on the north-east side.

The Santa Cruz ridge of white limestone overlooks the sea on the south-west coast. Near Malvern College, at about 1,800 feet, a boring for oil has recently been put down. It went down over 8,000 feet and met with a quite unexpected thickness of about 6,000 feet of white limestone, below which came rocks resembling lava and tuffs and near the base a dark green

serpentinous diabase, slightly slickensided. This is suggestive of some of the material below the Port Henderson ridge, at the Lazaretto.

Long Mountain is an elongate NW–SE dome of white limestone that overlooks Kingston on the east. Near Mona the rock appears to be broken up into great masses, as if it had been forcibly lifted and moved. On the north-east side it has raised up a typical series of August Town beds which dip steeply away off the mass.

On the north-east coast of Jamaica at Hope Bay, up the east side of the Swift River, there are thin bands of flint in the white limestone with *Lepidocyclina*. There is a small fault but it is the seaward side that has been thrust upwards and has displaced a layer of flint a distance of a few feet. This suggests that there has been pressure from the oceanic slope that has assisted the uplift while the adjacent sea bed on the north has gone down.

These various disturbances in Jamaica are not due to any pressure of rock from on either side, nor is there any evidence of intrusion from below. I attribute them to gravitational pull up of the massive white limestone aided by " sticky " metamorphism of parts of the rock below. As the island rose, later Tertiary sediments were deposited in the deepening sea around the coast. At the higher eastern end the massive white limestone tilts and contorts in various ways the later softer beds that happen to lie on its adjacent rising flank, while further away they lie flat or dip slightly seaward.

Barbados

Barbados is unique among islands. It stands well away from the Antillean arc, being 100 miles east of St. Vincent, the nearest volcanic island. It is surrounded by deep water, the 100 fathom line averaging about a mile off the coast. Jukes Brown thought it might have been forced up by some igneous mass below, but deep borings for oil to 10,000 feet go down only into Eocene Scotland beds.

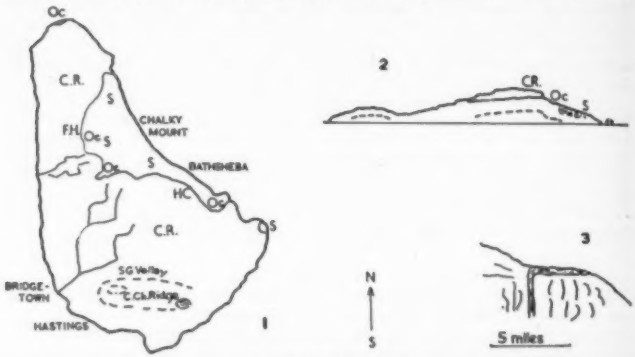
It is 21 miles north to south and 14 miles wide and was completely under the sea in Pleistocene times. The larger or main part on the north rises to 1,105 feet at Mt. Hillaby, formed of oceanic chalks; but a recent survey reports that Castle Grant, on coral rock, is higher. The southerly Christ Church anticline, extending east and west, is a later uplift and rises to 400 feet near its western end. Between these uplifts is the St. George's Valley, a depressed undulating area. The *Natural History of Barbados*, by Revd. Griffith Hughes (1750), gives the highest point of Barbados as 915 feet taken from high-water mark. This is about the position where Castle Grant now is, and if the old measurement is reliable, the island may have risen 100 feet in 200 years.

The oldest beds are shales, grits, and conglomerates well folded, striking generally east and west parallel with the northern range of Trinidad and Venezuela. They are middle to upper Eocene in age, now exposed in the Scotland area and a few small patches. They are shallow-water beds and contain both marine and freshwater shells, the latter including a large *Ampullaria* resembling some that now live in Central Africa, but not in South America. This and several river bivalves have lived in a large river draining some continental land mass that may have lain in the Atlantic in the direction of Africa. The pebbles, however, of the conglomerate are merely quartz and clay-ironstone and give no clue to the nature of the land.

The Scotland beds have been folded and contorted in an almost Alpine manner and at Chalky Mount (by the way, there is no chalk on it) a high and wide vertical faulted surface faces west. At the north and south ends of Barbados, the folding seems to be less acute than across the middle region. This folding cannot be attributed to any particular cause and we scarcely know which are the lower and which are the higher beds, but probably the Ragged Point grits in the south are the oldest. This folded mass of rocks does not seem to have been raised very high above the sea. The oceanics rest unconformably on its edges and in the lower beds *Hantkenina* is reported. As this is an Eocene genus the interval between the folding and planation

of the Scotland Series and deposition of the lower oceanics must have occurred during some interval in the upper Eocene.

Above the Scotland beds, the oceanics occur in patches. They are supposed to have been lain down in deep water. They now form the highest point of Barbados, Mt. Hillaby. At Bissex Hill, 800 feet, the formation is very soft and crumbles in the fingers, and consists of unbroken foraminifera and radiolaria. Though these beds have been raised below a heavy cover of limestone and coral rock, they are not compressed, and the small fossils are



TEXT-FIG. 2.—(1) A sketch map of Barbados indicating the zig-zag course of some of the stream gorges on the area covered by coral rock.

C.R. Coral rock. Oc. Oceanics. S. Scotland beds. S.G.V. St. George's Valley. C.Ch.R. Christchurch Ridge. H.C. Hackleston's Cliff. F.H. Fortress Hill.

(2) Section from near Hastings to Chalky Mount across the Christchurch Ridge and St. George's Valley and the main uplifted part of the island. The wave-cut terraces at higher levels have been further raised to form fault scarps.

(3) A section below Highgate Signal Station, on the south-west side of the Christchurch uplift, at about 250 feet altitude. The post-coral rock *Helix* bed has been turned down and caught between rising masses of coral rock. Just below 3 a perfect freshwater *Chilina* was found but where the bed is turned down all the shells are crushed and the rock sheared. The adjacent coral rock is fine-grained and shows surfaces movement of dislocation ; the sheared faces tend to bulge out in the direction of the sea and stand at acute angles to one another.

undamaged. This is always the case where the uplift has been purely vertical and suggests that the rise was a sort of release rather than compression. But at the edge of the rising terraces, where two forces have come into action the result is different. Below the terrace at Fortress Hill, on the north-west of Barbados, the base of the coral rock rests on oceanics. At this high level, further rise of the terrace has been considerable enough to expose a strip of the oceanic beds, which are here a dense yellow limestone, more or less veined, in which the globigerinae are crushed but still recognizable in places. The direct uplift has no crushing effect, but where a terrace has been further raised the combined uplift and cohesional mass attraction has produced hardening and crushing of the rock.

A similar effect has occurred in connection with the post-coral-rock *Helix* bed at the south end of the island, as will be described later.

Coral rock covers about four-fifths of Barbados and reaches 220 feet in

thickness. On the north-east side it has been removed and exposes the oceanic and Scotland beds, which have quite a different surface topography. The edge of the coral rock forms a curving scarp rising from sea-level on the north-east, going up to 1,000 feet, and sinking to sea-level again on the south. On the main part of the island, facing north, west, and south up to about 500 feet, the coral rock rises as a series of four or five successive wave-cut terraces. In front of the lower two of the terraces the terrain is flat as it would be to-day on a shore line, but at the foot of the higher terraces the surface is jumbled and has sloping surfaces as if the rock has been raised irregularly.

At the highest three terraces we see lines of vertical cliff scarps 80 or 100 feet high, separated by gaps and looking like a row of decayed teeth. At the foot of two of these, at Fortress Hill, and at another place, an extra rise has exposed the oceanics at the base. On the west side and on the south side, facing St. George's Valley, many steep gulleys, often with vertical sides, pass downwards. The vertical sides of these gulleys often go down to below the level of the base of the adjacent scarp that faces the sea and they often take sudden right-angle turns to the left or right on descending the slope and scarps. Schomburgk, writing on Barbados long ago, noticed these gulleys and said they are not the result of water action as there is not enough gathering ground above, and compared them with earthquake rifts in Calabria. They are evidently connected in some way with the mode of uplift of the island. They may be some sort of submarine topography that has come up.

The coral rock of Barbados had been practically all formed before the island uplift began. At the base, in several places from sea-level up to 1,000 feet and in the southern later uplifted ridge, I found a peculiar basal bed. The fossils in it are *Haliotis barbadensis*, *Pleurotomaria quoyana*, *Cavolinia*, *Terebratula*, and often thousands of *Amphistegeina*. These do not occur in the main coral rock above. *Haliotis* is not found on the western coast of the Atlantic to-day, but a deep water form was dredged off Florida, but was destroyed by fire at a Chicago exhibition. This basal bed may be Pliocene in age. The southern or Christ Church anticline is a later uplift aligned east and west. It has no deep gulleys and the soil is still black and not reddened by weathering as it is at levels above 600 feet. On the sides facing the sea it has wave-cut, often sinuous terraces and scarps, but these show less later uplifting than on the main part of the island. Nevertheless, the terraces have been further raised and have in the process involved some quite late post-coral rock beds. On the seaward sides of the Christ Church ridge there are some deposits later than the coral rock, which have been called the *Helix* beds. They are marly limestones with rolled pebbles of coral and marine shells, especially at lower levels, noticeably the large blotched periwinkle, *Livonia pica*. At all levels we find land shells, especially the now living *Helix isabella*, *Helicina* sp., *Buliminus* sp., and *Geomelania* sp. These beds were deposited in swamps a little above high-water mark as each terrace rose. This is the only formation on Barbados which, where involved, has been sheared and the fossils crushed and broken and this very late deposit is the one which we would least expect to have suffered thus.

On the south-east coast at Whitehaven this bed is unusually thick, some 20 feet, and rests on oceanics, but has been banked up against coral rock. The island had attained more or less its present state of erosion before the *Helix* bed was deposited. Even so, it is not quite recent because here and at Silver Sands it is being undercut by the sea. The *Helix* bed was deposited on each terrace as it came up, so each higher terrace is older than the one below. At Silver Sands it contains marine gasteropods as well as *Helix*; it forms a veneer on the coral rock and is banked up against the base of a stack of that rock. It dips gently seawards, but at the next higher terrace it dips more steeply. Behind the Marine Hotel marl about 6 feet thick has been caught up between masses of coral rock and contains crushed *Livonia* and land shells. Further east, at the base of the third scarp, is a band of broken *Livonia* in crushed marl, the mottled outside of the shells contrasts with the pearly interior on the smashed specimens.

At the foot of and up the slope of the terrace below Highgate Signal Station, at about 250 feet, one sees the veneer of post-coral-rock passing up the slope on the surface; but it suddenly turns vertically downwards and becomes involved between masses of coral rock, which themselves show cleaved surfaces. In a quarry here it can be traced to a depth of over 20 feet, it is quite vertical, about 18 inches thick, and contains a few marine shells and plentiful land mollusca. These are crushed to pieces but one can recognize *Helix*, *Helicina*, and *Geomelania*. Just above the point where it turns down I found a sharp-pointed, smooth freshwater shell, like a *Limnaea*, but with a pleated columella. It is not crushed and looks like some form of Chilina now living in Peru and Chile but apparently not on Barbados.

These vertically involved *Helix* beds occur only near the western or more highly uplifted part of the Christ Church ridge where it rises to 400 feet. They are not mere fissures filled with late material because the bed is distinctly stratified as it is before it turns down into the coral rock.

The top of the broad Christ Church ridge is undulating with swallow holes formed by solution of the coral rock. On the north side it slopes irregularly down to the St. George's Valley and there are no wave-cut terraces as there are on the seaward sides. How then did it come up? The coral bank that gave rise to Barbados started to grow in deep water; the fossils in the basal bed died out and the reefs grew upwards till they came near to the surface. It may then have come under the influence of some upward tidal pull. On the main part of the island the upward urge has been strong enough to form the terraces into lines of vertical cliffs. On the lower Christ Church ridge the upward urge was less strong, but the terraces, so to speak, chased one another up, with the result that at the inner angle of the higher terraces the post-coral-rock beds have been caught up and sheared and the enclosed shells broken into pieces.

The north-east end of Barbados is flat, the coral rock is thin and has not the usual basal bed. Its growth here seems to have been hindered by being mixed up with underlying oceanic chalk. It has stayed low, while just to the south where the rock is massive it rises in a series of terraces.

All these features suggest that gravitational vertical pull-up is a powerful though distantly acting force and the soft material below had to follow up beneath the heavy cover as a sort of release and in consequence is uncrushed. The cohesional side pressure is a less powerful but more immediate force and the two acting together produce a hardening and crushing effect.

The whole island is an uplift and all the faults are double up-faults and the rise continued when the island was well above sea-level and presumably out of the reach of any pressure of rock from the sides.

The age of cataclysmic geology is suppoed to be over, but is it? At Hackles-tons Cliff, 997 feet above the sea, on the south-east of the coral rock escarp-ment, one looks down on to Bathsheba, about a mile away on the coast. There are many undercut masses of coral rock on the shore and I used to think they had rolled down from the escarpment. Examination of most of them shows they are rooted *in situ* on Scotland beds and have the usual *Amphiste-gina* bed at the base. It looks as if the coral rock had been forcibly dragged up and raised to 900 feet in the distance of a mile, but no doubt the process was slower than would appear.

Trinidad

The northern range of Trinidad, 45 miles from east to west, rises to just over 3,000 feet. It is an amazing display of a geological late-bedded series of sandstone, limestone, and shale, very largely altered to quartz, calcite, chalybite, with haematite, talc, sericite, gypsum, etc., fossils in the less altered parts in the south-west at Laventille and on the north-east at Toco date from Upper Jurassic to Upper Cretaceous.

Lenses among the schist consist of crystalline calcite, chalybite, and quartz, and often have ragged interior cavities lined with talc, but at the edges the grit frequently remains unaltered, passing abruptly into the crystalline material in the interior. It is at these narrow edges of the lenses that one

might have expected the pressure to have been greatest. Another noticeable feature is that the quartz forms round the calcite rhombs as narrow partitions like the sides of a box, as if the quartz had crystallized out later than the calcite, as it does in a granite with respect to the feldspar crystals. In one place I found ferruginous grit turning into quartz crystals and talc near Morvant. The northern range is much folded and contorted but not compacted. It looks like a case of metamorphism without apparent pressure. There is only one minor occurrence of igneous basic rock, at Sans Souci, on the north-east coast. The northern range rises to three times the height of the central range, 20 miles to the south. This is formed of Cretaceous and early Tertiary rocks quite unmetamorphosed. A boring at Mt. Harris to 10,000 feet was still in dark Barremian shale only slightly slickensided.

The nearness of the northern range to an old shore line and the drawing up may have induced penetration by metamorphosing liquids and gases and caused its extra rise. I should prefer to attribute the gravity diminution over mountains to some such loosening or porosity rather than to any hypothetical down folding of lighter rock below them.

New Zealand

This is a country of great uplifts of the massive pre-Tertiary rocks and involvements of very thick covering beds, generally aligned parallel to the present coast lines, suggesting some influence of the sea. There is no evidence of any rock pressure from either side and apparently there is no granite claiming to be Tertiary in age. The most ancient rocks occur in the Nelson Province, Fiordland, and the Bluff on the south. A long fault separates them from the high Alpine backbone, which consists of Maitai or Permo-Carboniferous and Triassic beds, which are very thick; the upper Trias is estimated at 20,000 feet. These become metamorphic, principally in Otago. The covering beds range from middle Cretaceous to Pliocene.

In the Kaikoura Ranges, on the north-east of the South Island, and the Clarence Valley, the NE–SW ranges of the Kaikoura rise from 8,500 to 9,500 feet and over-top the Cretaceous and Tertiary beds of the Clarence and Awatere Valleys. The grain or structure of the Permo-Carboniferous of the Kaikoura is said to be independent of the direction of the involved strips. In the Clarence Valley, the newer or Amuri beds are on the west, dipping towards the more elevated Kaikoura Range.

On the north shore of Lake Whakatipu, at Bob's Cove, is the great involved strip of Oamaru Tertiary covering beds, about 1,500 feet thick. It extends to the north for about 25 miles and crosses Mt. Silverhorn at an altitude of 5,300 feet, where it has become narrowed to 75 to 100 feet, and dips 75° W. This slice of Tertiaries is enclosed by schist. On the lake I thought the highest beds were on the west and the schist must have risen much higher on this side than on the east, the side on which the Oamaru beds rested. Fossils are only moderately broken. At Lake Te Anau, further south, the Tertiaries are tilted up on the flank of mountains of older rock of each side of the lake.

New Zealand is a type area of what is called block faulting, which I prefer to call block uplift or pull-up of more massive beds, leaving the softer and more easily denuded strata below but tilting them in various directions.

The outbreak of volcanoes in the North Island seems to have had a pacifying effect so far as further uplift is concerned. The dormant cone of Mt. Egmont, in the south-west of the North Island, has a great thickness of Miocene beds on its flank and probably beneath it, they were bored to 8,260 feet.

A number of these features were mentioned in a paper I had printed by Messrs. B. T. Ord, of West Hartlepool, in 1950, entitled " New Zealand and My Forbidden Theory of Mountain Uplift ".

Reduction in Volume of Rocks by Metamorphism

In Devonian slates at Holbeach, in North Cornwall, the one-time thick spirifers are reduced to ghost-like films of sericite, while Crinoid ossicles in the same piece show that the bed was once calcareous.

At Os, in Norway, in the Bergen Arches, masses of Ordovician corals are slightly flattened while bands of mica schist pass through the actual coral.

In Jamaica, at Moy Hall, on approaching the serpentine at Arntully, conglomerate with limestone pebbles enclosing Rudist remains and Foraminifera occur. Patches of serpentine develop while the pebbles become reduced in size till they are mere pellets. The pebbles become impregnated from the outside inwards by green infiltration and in some pieces are drawn out into streaks but still retain fossil traces, in a sort of ophicalcite.

The wholesale removal of calcite is obvious, but I can assign no reason for it, except that the process is chemical and mineralogical rather than dynamical. Such contraction occurring through a considerable thickness of rock could account for local folding and thrusting as the mass becomes drawn together as it is drawn upwards.

C. T. Trechmann.

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6th March, 1958.

ULTRABASIC PILLOW LAVAS FROM CYPRUS

Sir,—Preliminary accounts of the Troödos massif and igneous complex were given by the writer in *Nature*, 1952, and in the Transactions of the XIXth International Geological Congress (1952), published in 1954, as well as in unpublished official records. The subdivision of the massif into its main groups and the recognition of more than one series of lava flows had in fact been accomplished and demonstrated by the writer before 1953; since when the Geological Survey has been steadily continuing its investigation of the island.

It is incorrect, therefore, that in the second paragraph of his paper " Ultrabasic Pillow Lavas from Cyprus " (*Geol. Mag.*, xcv, No. 3, 1958), Mr. I. G. Gass should ascribe this early work to the present organization; while he omits my two short but fundamental papers of 1952–54 from his bibliography. In fact, the general reconnaissance of the whole area and pioneer mapping of over 250 square miles of this rough and then geologically unknown region was done by the writer (1950–53) with the assistance of Mr. R. A. M. Wilson during 1952 and the end of 1951.

There are some further points of interest which have not yet received the attention they deserve.

Mr. Gass records a difference of opinion as to whether the Diabase Formation represents a huge series of north-south dykes or a set of isoclinally-folded lava-flows. Both of my papers cited above give the evidence on which I named this formation the " Folded Diabase ", whose component sheets vary from a few centimetres to a metre or so in thickness, and whose total breadth of exposure across the strike is some 50 miles. The strike does not vary more than a few degrees either side of north and south, and is frequently north-north-west, thus lining up with the Red Sea direction. On the evidence I have interpreted the structure as a great anticlinorium of which the heart has been filled by the basic plutonic core described. There is a lot of dyke-matter intruded lit-par-lit into this diabase; but if the whole thing is a huge series of dykes in groups inclined at various angles it becomes enormously difficult to explain the structures by any theory of faulting; or the emplacement of a pack of dykes of such small thickness and huge extent like the leaves of a book. Each dyke must have had time to solidify before an adjacent one came in beside it and displaced the existing wall-rocks for dozens of miles all told. The dips of the various limbs of the supposed folds run as a rule between 45 and 60 degrees either to east or west; and the turnover at the bottom of a syncline is unusually sharp if not angular, while the slopes from valley-bottom to crest may be as uniform as a roof for several thousand feet. But this is not inconsistent with the rigid, non-plastic, competent character of the diabase which shows low-grade metamorphism.

I have not yet heard the argument counter to the folding theory and should welcome knowledge of it.

The diabase and its relationships were, however, so unusual, if not unique, that every effort was made to look elsewhere for a parallel example which might throw further light on them. The geological maps of Turkey (scale 1 : 800,000) were not particularly helpful because the older formations were so heavily covered by post-Triassic material; though they did indicate the presence of Palaeozoic and metamorphic rocks on the Turkish coast north of Cyprus. So far as could be ascertained there was no parallel in Palestine or the Sinai Peninsula; but Dubertret's map of Syria (1 : 500,000) suggests an extension on the mainland of what may be called Troödos conditions. The Qizil Dagh massif which forms the promontory of the coast north-west of Antioch shows a great central sack-shaped core of pyroxenites, peridotites, and serpentines (with some chromite) set in a wide girdle of gabbros and diorites, which are stated to grow finer in grain as their outer margin is approached. The Qizil Dagh exposes a much larger area of these rocks than is seen at Troödos, the peridotites alone covering 250 square miles. In the short explanation covering Dubertret's map, a batholithic character and a thickness of at least thousands of metres is assigned to the ultrabasic core; but there is no mention of anything comparable to the Diabase, or of andesitic or spilitic lavas surrounding the massif. I am much indebted to M. Dubertret for sending me his maps and some personal observations. He alludes to the fine grey sandy type of weathering endured by the gabbros, exactly as in Cyprus, where erosion produces rounded slopes and relatively depressed areas in contrast to the jagged outcrops of Folded Diabase, which generate a reddish-brown soil. It would seem from the description that the Troödos and the Syrian coastal plutons belong to the same province and period.

The surprising homologue of Cyprus comes from the other side of Africa: the Canary Islands, and this is the only parallel that I am aware of. One of these, Fuerteventura, was described in some detail by J. Bourcart and A. Jeremine in the *Bull. Volc.*, Series II, vol. iii, 1938. I have not visited the island, and the following are salient points from the French paper.

Geologically, the oldest rocks are Bourcart's " trapps " [*sic*], which are sheeted (" des bandes successives ") and highly folded. They include spilites, andesitic lavas, and basalts. (There is in fact some rare spilitic material in the Folded Diabase of Cyprus, in the west end of the island, as well as in the later lavas, which to my mind makes it certain that the diabase succession originated as flows.) Olivine is recorded in the " trapps ", also amphibole and epidote, which are a feature of metamorphism in the diabase of Cyprus. In Fuerteventura there is a central core of gabbro and syenite intrusive into and surrounded by these " trapps ", which antedate the plutonic core. Finally, the eroded and upturned edges of the " trapps " are overlain by basalt flows with complete unconformity: in Bourcart's words, " en totale discordance." The late flows are stated to be of post-Miocene age, but distinction is made between an earlier and a later series. No post-Miocene lava is known in Cyprus.

Both physically, geologically, and so far as is known at present petrologically, Fuerteventura is a close counterpart of the Troödos block; according to Bourcart's and Jeremine's account, their " trapps " give rise to exactly the same topography as the Folded Diabase; the figures and certainly the geological section on p. 66 of their paper might have been taken from Troödos. The geographical setting of each island in relation to the African coast is similar; the sequence and relationship of the four groups of rocks: Folded Diabase, Basic Plutonics, and discordant early and late lavas, are matched; the types are similar and there appear to be points of resemblance in metamorphsim and structure. Serpentine is not recorded at Fuerteventura; but the Canaries are less deeply eroded and contain later lavas than Cyprus.

Such a resemblance between volcanic islands off the African margin, albeit on opposite sides of the continent, seems more than fortuitous. Troödos is no longer unique. Is there an explanation common to both? Are we

looking at isolated scraps of a regional phenomenon generally concealed by the sea around the continental margin? In view of the very large positive gravity anomaly known in Cyprus, it would be of great interest to get observations from Qizil Dagh and the Canaries and compare them.

The formation of pillow-lavas seems to mean no more than the discharge of a flow into the sea, not necessarily into deep water; on the northern side of the Troödos there is certainly one example of a flow a few feet thick with marked columnar jointing merging into pillows without jointing, presumably as it moved off-shore.

D. W. Bishopp.

Johannesburg.

22nd July, 1958.

PELAGIC FORAMINIFERA IN THE TERTIARY OF VICTORIA

Sir,—I was extremely interested to read the recent account (July–August, 1958) by Alan Carter of the planktonic foraminifera of the Victorian Tertiary.

For the last two years I have been working on foraminifera from a 1,200 ft. sequence of marine rocks from the Lakes Entrance Oil Shaft, Gippsland, Victoria. Samples were collected at every 4 feet, below 212 feet, by Miss I. Crespin, and were made available to me by the Bureau of Mineral Resources, Canberra.

I would like to comment on some of the ranges of some of the foraminifera referred to in Carter's paper and compare them briefly with those found in the shaft.

(1) The initial appearance of *Globigerina ciperoensis ciperoensis* Bolli is 64 feet above that of *Globoquadrina dehiscens* (Chapman, Parr, and Collins) and its extinction is 172 feet before the initial appearance of *Orbulina universa* d'Orbigny. It seems, therefore, to have a shorter range than that indicated in his Table 1 (p. 299), more comparable to that recorded in Trinidad (Bolli, 1957). The subspecies *Globigerina ciperoensis angustisuturalis* Bolli has a still shorter range.

(2) *Globigerinoides bispherica* Todd appears 172 feet after the initial appearance of *Globigerinoides triloba* Reuss, and 64 feet before that of *Orbulina universa* d'Orbigny. Again, it is suggested that this species has a much shorter range than Dr. Carter indicates. It is sometimes confused with the large forms of *Globigerinoides triloba* Reuss *immatura* Le Roy, but the emended description of Blow (1956) does help in its diagnosis.

(3) *Globigerina ampliapertura* Bolli is found before the appearance of *Globigerina ciperoensis ciperoensis* Bolli, and prior to the publication of Bolli's paper (1957) this Upper Oligocene/Lower Miocene form was called *Globigerina apertura* Cushman. This latter name is now restricted to forms which occur in the Middle and Upper Miocene only.

(4) *Globigerinoides rubra* d'Orbigny is very rare, occurring in only four samples scattered over 144 feet.

(5) *Orbulina universa* d'Orbigny appears 20 feet after *Candorbulina universa* Jedlitschka (= *Orbulina suturalis* Bronnimann) and *Orbulina bilobata* (d'Orbigny) (= *Biorbulina bilobata* Blow) 12 feet later. Blow's (1956) evolutionary series is present in all its detail and it may be of some interest to note that the evolution of *Orbulina universa* d'Orbigny from *Globigerinoides triloba* (Reuss) takes place in 236 feet of marly Bryozal limestone.

(6) *Globorotalia barisaensis* Le Roy occurs, but the keeled *Globorotalia fohsi* lineage is not present, which seems to confirm Carter's views (p. 302). Probable specimens of *Catapsydrax dissimilis* (Cushman and Bermudez) and *Globigerinatella insueta* Cushman and Stainforth occur in the lower part of the shaft but are too rare to be considered as zone fossils. The important fact is that their ranges seem to correspond to those in Trinidad (Bolli, 1957).

It is hoped to publish shortly a detailed account of the ranges of some

fifty species and subspecies of planktonic foraminifera found in the shaft as a further contribution to the intercontinental correlation of the Tertiary rocks.

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31st August, 1958.

DEVELOPMENT OF LINEATION IN COMPLEX FOLD SYSTEMS

SIR,—Mr. P. A. Hill expresses the view in his letter (*Geol. Mag.*, 1958, xcv, 351), that a paper (ibid., xciv, 1–24, 1957) by Clifford, Fleuty, Ramsay, Sutton, and Watson is, in parts, of " spurious accuracy ", " statistically invalid ", " over-written ", and expressed in " jargon ". When Hill goes on to add " that these remarks are in some ways unfair, as they apply to many other workers " I am tempted to comment that perhaps we are all out of step except George.

" Spurious accuracy." Hill criticizes " dip symbols of 31°, 59°, 71°, etc." on our fig. 8 in the paper " a map of country where variation in dip is extreme ". There are in fact no dip symbols on this map, but I will take it that Hill means structural observations in general. I had thought that the view that it was worthless to make accurate measurements in such ground was dying out. Rightly or wrongly our procedure has been to take large numbers of observations and to make each as accurate as we could. By doing this one can hope to find out whether there is system in the variations. Ramsay's field map of the ground covered by fig. 8 contains over 4,000 structural measurements. The analysis and presentation of such large masses of data raises problems. In the paper we used three methods of presentation—stereograms (figs. 6, 10, 11) ; sketch-maps showing generalized lines of strike with the directions of dip indicated (figs. 3, 4, 6, 10), or generalized directions of lineations (figs. 7, 10, 11) ; maps showing observed values where there was some special reason for publishing these (fig. 8). One of the reasons for drawing fig. 8, criticized by Hill, was to show the *distribution* of two sets of linear structures, to demonstrate how one set survives near the axis of an early fold, but is largely destroyed on the limbs. It is disheartening to find that Hill, as a serious critic of the paper, states that these clearly labelled symbols for lineations represent dips of bedding planes or foliations.

Hill states that our fig. 10 is " statistically invalid ". He claims that the distribution of 250 foliation readings shown on this figure is not given. The information appears, however, on p.16, lines 9–11. Hill also claims that the scatter of these readings is not shown. It is, however, shown by the stereogram, fig. 10*b*. This stereogram also indicates that the fold axis in the ground discussed by Fleuty is not bent in the manner Hill suggests. Although Hill has failed to grasp two of the facts shown by this stereogram he is content to end his letter with the *ex cathedra* remark (after no discussion of the matter at all) that stereographic projections are used as window dressing.

" Over-writing." Hill asks why 26 words are needed to say that a fold plunges steeply. This seems a reasonable question until one turns up the reference (p. 16, lines 1 and 2) and finds that the sentence says nothing about the amount of plunge but describes the form and attitude of a rather unusual fold.

"Jargon." Here I am on delicate ground. What seems all right to one is jargon to another, but I am surprised at the terms Hill objects to. Bailey's terms *antiform* and *synform* have been in use for a quarter of a century and describe succinctly the form of folds in ground where the rocks are inverted or the succession is not known. I am sorry they are strange to Hill. We used hinge in the sense it has been used by Bailey (*Tectonic Essays*, 1935, pp. 51, 91, 156) and as defined by de Margerie and Heim (*Les dislocations de l'écorce terrestre*, Zurich, 1888. French text, pp. 50 and 51).

I find it difficult to comment on Hill's discussion of the main purpose of the paper as he seems so frequently to have got hold of the wrong end of the stick or to have missed the relevant passage in our text. Here are some examples of what I have in mind. Hill complains that we do not seriously consider "rotation simultaneously with or during the closing stages of folding." Yet pages 5–8 of the paper are concerned with movements of varying complexity which we consider to have occurred simultaneously.

On page 8 (last para.) and on page 9 (see also fig. 5) we deal specifically with the effects of renewed deformation during the closing stages of folding. Incidentally Hill's comments on our fig. 5 are particularly curious for we specifically state in the text that the wrinkles are not related to the fold depicted, but are later than it.

Hill appears sceptical about our recognition of earlier and later structures. When one set of structures cuts across another or is superimposed upon another, it appears to us reasonable to accept that one is later than the other. Pages 11 to 19 deal with such matters and the accompanying figures illustrate them. It appears to me that Hill has misread one of the most important figures in this part, as we have already seen (fig. 8) ; he says himself that he does not see the purpose of another (fig. 9) though this seems straightforward enough. He has failed to see the strike lines clearly indicated on fig. 6 and has missed the information fig. 10*b* provides. His note concerning the Tarvie syncline and our fig. 7, placed in brackets in his letter, suggests that a long passage (para. 3 of our page 12) dealing with the same matter has escaped him. How seriously can one take the comments of a reader who goes through a paper in so slap-dash a fashion?

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6th September, 1958.

DERIVED AMMONITES IN BASAL CRETACEOUS CONGLOMERATE

SIR,—In the course of a recent field class in Northern Ireland, one of my students, Mr. J. A. Hirst, discovered in the Basement Conclomerate of the Cretaceous a *remanié* Middle Lias ammonite. The precise locality was the roadside section above Binvane Farm, Murlough Bay. The specimen has been identified by Dr. M. K. Howarth as *Pleuroceras transiens* (Frentzen) which in Britain is known only from a few feet of strata near the junction of the *margaritatus* and *spinatum* zones in the Middle Lias of Raasay. Although there is a record of derived Upper Lias fossils in the Cretaceous conglomerate (Hartley, J. J., 1933, *Irish Naturalists Journ.*, vol. iv, p. 238), this is, so far as I am aware, the first record of Middle Lias forms. The specimen is now in the Geological Survey Museum (GSM 96788).

H. C. VERSEY.

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9th September, 1958.